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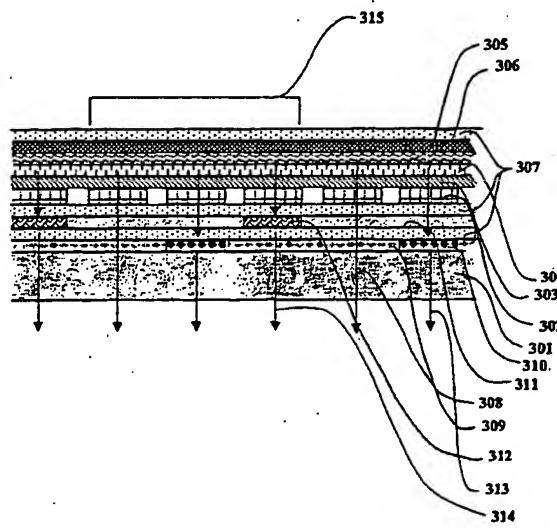
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- (71) Applicant (for all designated States except US): EMAGIN CORPORATION [US/US]; 2070 Route 52, Hopewell Junction, NY 12533 (US).
- (72) Inventor; and
- (75) Inventor/Applicant (for US only): PICHLER, Karl [AT/AT]; Haupstrasse 3, A-8911 Admont (AT).
- (74) Agent: ZISK, Matthew, B.; Skadden, Arps, Slate, Meagher & Flom LLP, Four Times Square, New York, NY 10036 (US).
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(54) Title: METHOD OF PATTERNING COLOR CHANGING MEDIA FOR ORGANIC LIGHT EMITTING DIODE DISPLAY DEVICES



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(57) Abstract: The present invention relates to methods of patterning OLED organic layers using photo-oxidation. Specifically, the present invention relates to methods of patterning color changing material layers using light and ambient oxygen, together with a photomask, to photobleach unmasked areas of the layers. In particular, color changing materials can be patterned without physically removing any material from the layer. The method produces photobleached areas of the color changing material layers that do not absorb or emit light and that are substantially transparent to visible light. In particular, the methods of the present invention are useful for making high resolution, full-color OLED display devices comprising patterned fluorescent color changing material layers to create red and green sub-pixels starting from a monochromatic blue-emitting OLED display device.

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## TITLE OF THE INVENTION

**METHOD OF PATTERNING COLOR CHANGING MEDIA FOR ORGANIC  
LIGHT EMITTING DIODE DISPLAY DEVICES**

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority on Provisional Patent Application No.

10 60/222,325, filed August 1, 2000.

## BACKGROUND OF THE INVENTION

Organic electroluminescent devices, also known as organic light emitting diode ("OLED") devices, have been known for approximately two decades. All OLEDs work on the same general principles. One or more layers of semi-conducting organic material are sandwiched between two electrodes, an anode and a cathode. An electric current is applied to the device, causing electrons to move into the organic material(s) from the cathode and positive charges, typically referred to as holes, to move into the organic material(s) from the anode. The positive and negative charges recombine in the electroluminescent medium (*i.e.*, the emitter layer) and produce photons. The wavelength of the photons, and consequently the color of the emitted light, depends on the electronic properties of the organic materials in which the photons are generated. The electronic properties of the organic materials are in turn dictated by their chemical structures.

Therefore, the color of light emitted from an OLED device may be controlled by the selection of the organic materials in the emitter layer. Specifically, the precise color of emitted light can be controlled by the selection of host materials and dopants in the emitter layer. By changing the kinds of organic solids making up the emitter layer, many different colors of light may be generated, ranging from deep blue to red. In addition, color filters and color changing media may be used to alter the color of light emitted from the emitter layer of an OLED.

An OLED may be designed to be viewed either from the "top" (*i.e.*, from the face distal to the substrate), which is referred to herein as "up-emitting," or from the "bottom" (*i.e.*, through the substrate), which is referred to herein as "down-emitting." Whether an OLED is designed to emit light through the top or the bottom, the

structure between the viewer and the light-emitting material should be sufficiently transparent to allow the emitted light to pass. In many applications, it is advantageous to employ an up-emitting OLED. This permits an OLED to be built on top of an opaque silicon driver chip, e.g., for active matrix addressing.

5       OLED displays are typically composed of a two-dimensional matrix of pixels, each of which comprises an OLED. Such displays generally include an addressing circuit for activating the matrix of pixels in either an active or a passive manner. In a typical passive matrix-addressed OLED display, numerous OLEDs are formed on a single substrate and arranged in groups in a regular grid pattern. Several OLED 10 groups forming a column of the grid may share a common cathode, or cathode line. Several OLED groups forming a row of the grid may share a common anode, or anode line. The individual OLEDs in a given group emit light when their cathode line and anode line are activated at the same time. In contrast, in an active matrix OLED display, the row and column structure is build into the substrate using standard semiconductor fabrication techniques. In this case, the substrate has an array of discrete 15 electrodes, each one corresponding to a point in the matrix.

      OLED displays are emerging as a viable design choice for use in small products, especially small portable electronic devices, such as head-mounted displays, pagers, cellular and portable telephones, two-way radios, data banks, etc. OLED 20 arrays are capable of generating sufficient light for use in displays under a variety of ambient light conditions (from little or no ambient light to bright ambient light). Furthermore, OLEDs can be fabricated relatively cheaply and in a variety of sizes from very small (less than a tenth millimeter in diameter) suitable for microdisplay devices to relatively large (greater than an inch) so that OLED arrays can be 25 fabricated in a variety of sizes. Also, OLEDs have the added advantages that their emissive operation provides a very wide viewing angle. In addition, OLEDs have a low activation voltage (about 5 volts), a fast response when the emitter layer is thin, and high brightness in proportion to the injected electric current.

      An OLED display may be monochromatic, that is, each pixel comprising the 30 display emits light of the same color. Alternatively, various pixels of an OLED display may emit different colors. A full-color OLED display is formed from an array of pixels comprising a red, a green and a blue sub-pixel. The sub-pixels in any particular pixel can be activated in various combinations to generate an entire spectrum of colors.

Although substantial progress has been made in the development of full-color OLED display devices, additional challenges remain. There are drawbacks to the existing approaches to the fabrication of OLED displays. For example, one approach to generating full-color OLED displays is to provide a self-emissive pixelated display, 5 with adjacent OLED sub-pixels emitting red, green and blue light. This approach, in principle, allows the best possible performance because no light is lost through absorption by a filter or color changing material. However, it requires precise shadow mask fabrication and alignment for vacuum deposition of low molecular-weight materials. Such precision in the fabrication of shadow masks is difficult for 10 miniature, high-resolution displays with pixel sizes in the range of several microns.

A second approach for making full-color OLED displays employs OLEDs that emit white light combined with color filters that are precisely aligned over each 15 OLED. Certain wavelengths of light are filtered out by the filters, with the result that the various color filters generate red, green and blue light for the sub-pixels. The use of color filters can be inefficient, however, because the filters inevitably absorb some light.

A third approach for making full-color OLED displays is to use a 20 monochromatic OLED array with color changing materials (instead of color filters) aligned on top of the pixels. Color changing materials work by absorbing light of higher wavelength (e.g., blue light) and then emitting light of lower wavelength by 25 fluorescence or phosphorescence (photoluminescence) (e.g., red or green light). The use of color changing materials is known in the art (see e.g., C. Hosokawa *et al.* (1997) J. SID 5(4):331; U.S. Patent No. 5,126,214 assigned to Idemitsu Kosan Co., Ltd.; and U.S. Patent No. 5,294,870 assigned to Eastman Kodak Co.).

The latter two approaches are technologically feasible given the present state 30 of the art because all pixels emit the same color and the filter media can be patterned and aligned with each OLED to form the different color sub-pixels. When the relevant layers have high quantum efficiency of photoluminescence and internal losses are minimized, the third approach provides higher efficiency.

Nevertheless, the use of color changing materials also has drawbacks. Most materials used as color changing materials have broad emission photoluminescence spectra that require the use of optical filters for spectral correction, *i.e.*, to insure that each sub-pixel emits red, green or blue light in a narrow wavelength range. The use of

optical filters in addition to the color changing materials may introduce additional loss of intensity of emitted light.

In addition, existing techniques for patterning the color changing material layers have limitations. For example, etching requires relatively thick color changing material layers, which results in a display having coarse resolution. A photolithography process may not be compatible with the highly photoluminescent organic color changing materials or with photo-resist solution, developer, etch solution or plasma. Even if standard photolithography is possible, it requires a large number of steps and is thus quite costly.

10 There is clearly a need for a method of patterning color changing material layers for high-resolution, full-color OLED display devices.

Discussion or citation of a reference herein shall not be construed as an admission that such reference is prior art to the present invention.

## 15 BRIEF SUMMARY OF THE INVENTION

The present invention relates methods for fabricating color OLED display devices. Preferably, the present invention relates to methods for fabricating full-color OLED display devices, which are those devices having red, green and blue sub-pixels that can be activated in any combination to produce any color in the visible light spectrum.

20 The present invention relates to methods for patterning thin fluorescent color changing material ("CCM") layers using photo-oxidation in the presence of oxygen and a photomask. Preferably, the oxygen is ambient oxygen. The patterning occurs without the physical removal of color changing materials from the layers. The present invention further provides a protective layer between subsequent color changing material layers in order to prevent the photo-oxidation patterning of underlying layers during patterning of the topmost layer. Photo-oxidation patterning leaves the fluorescence of the materials in the protected parts of the layer intact while making the photo-oxidized parts non-fluorescent or with very low fluorescence. The present invention allows for the patterning of layers directly on OLEDs without destroying the underlying layers. The resulting displays can have very high resolution, *i.e.*, small pixel size.

25 The methods of the present invention are simple and economical. Furthermore, the methods can be used to fabricate color OLED display devices using

a wide variety of standard materials and standard mask-aligners and photo-exposure equipment. In some embodiments, the methods of the present invention utilize a one-step exposure of the color changing material layers to ultraviolet light.

In a particularly preferred embodiment, the present invention can be used to 5 fabricate high-resolution, full-color OLED display devices having pixels comprising red, green and blue sub-pixels. More preferably, the devices have very small pixel sizes and high quantum efficiency of photoluminescence (and therefore, high brightness) and may be down-emitting or up-emitting displays.

The methods of the present invention allow for patterning of color changing 10 materials without removal of any of the material in the layers. As a result, very thin color changing material layers can be used, which prevents loss of light and contrast. In addition, the methods of the present invention allow for the preservation of the flatness of the patterned layers so that high-resolution color OLED displays can be fabricated.

15 In a first embodiment, the present invention relates to a method for patterning a first layer comprising a first color changing material, the method comprising: (a) exposing at least one area of the first layer to light and oxygen and leaving at least one area unexposed; and (b) covering the at least one unexposed area with a protective layer, wherein the first color changing material in the at least one exposed area 20 becomes substantially transparent to visible light and substantially non-photoluminescent after the exposing step.

In a second embodiment of the present invention, the method further comprises the steps of: (c) forming a second layer comprising a second color changing material over the first layer; and (d) exposing at least one area of the second 25 layer to light and oxygen and leaving at least one area unexposed, wherein the second color changing material in the at least one exposed area becomes substantially transparent to visible light and substantially non-photoluminescent after the exposing step, and wherein the two unexposed areas are not aligned.

30 In a third embodiment, the present invention relates to a method for patterning a layer comprising a color changing material, the method comprising: (a) aligning a photomask over the layer, the photomask comprising a first area that is transparent to light and a second area that absorbs light; (b) shining light through the photomask onto the layer in the presence of oxygen and leaving at least one area unexposed; and (c) covering the at least one unexposed area with a protective layer, wherein the area

of the layer under the first area of the photomask is exposed to light and oxygen, wherein the area of the layer under the second area of the photomask is not exposed to light and oxygen, wherein the color changing material in the exposed area becomes substantially transparent to visible light and substantially non-photoluminescent after the exposing step, and wherein the color changing material in the unexposed area is substantially non-transparent to visible light and substantially photoluminescent after the exposing step.

- 5 In a fourth embodiment, the present invention relates to a method of fabricating an up-emitting full-color OLED display device comprising the steps of:
- 10 (a) providing a monochromatic OLED display device having a plurality of bottom electrode elements and a surface through which light is emitted; (b) depositing a first layer comprising a first color changing material on at least a portion of the surface; (c) aligning at least one light absorbing area of a photomask above the first layer with a first electrode element of the monochromatic OLED display device; (d) exposing at least one unmasked area of the first layer to light shone through the photomask in the presence of oxygen to leave a first color changing region in a first patterned layer aligned with the first electrode element; (e) depositing a first protective layer over the first patterned layer; (f) depositing a second layer comprising a second color changing material on the first protective layer; (g) aligning at least one light absorbing area of a photomask above the second layer with a second electrode element of the monochromatic OLED display device; (h) exposing at least one unmasked area of the second layer to light shone through the photomask in the presence of oxygen to leave a second color changing region in a second patterned layer aligned with the second electrode element; and (i) depositing an encapsulation layer over the second patterned layer, wherein the at least one area of the first layer and the second layer under the at least one light absorbing area of the photomask are masked, and wherein the at least one unmasked area of the second layer overlies the first color changing region.
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- 25

#### BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

- 30 Figure 1 shows a monochromatic OLED display device.
- Figure 2 shows an up-emitting full color OLED display device.
- Figure 3 shows a down-emitting full color OLED display device.
- Figure 4 shows a first step in a method according to the present invention.
- Figure 5 shows a second step in a method according to the present invention.

Figure 6 shows a third step in a method according to the present invention.

Figure 7 shows a fourth step in a method according to the present invention.

Figure 8 shows a fifth step in a method according to the present invention.

Figure 9 shows a full-color OLED display device made by a method according  
5 to the present invention.

Figure 10 shows another embodiment of a full-color OLED display device  
made by a method according to the present invention.

Figure 11 shows one configuration of an OLED display device comprising  
color changing material layers and made by a method according to the present  
10 invention.

Figure 12 shows another configuration of an OLED display device comprising  
color changing material layers and made by a method according to the present  
invention.

Figure 13 shows another configuration of an OLED display device comprising  
15 color changing material layers and made by a method according to the present  
invention.

Figure 14 shows yet another configuration of an OLED display device  
comprising color changing material layers and made by a method according to the  
present invention.

20 Figure 15 shows a first step in a method of the present invention.

Figure 16 shows a second step in a method of the present invention.

Figure 17 shows a third step in a method of the present invention.

Figure 18 shows a final step in a method of the present invention.

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#### DETAILED DESCRIPTION OF THE INVENTION

"Bottom electrode," as used herein, means an electrode that is deposited  
directly onto the substrate.

"Top electrode," as used herein, means an electrode that is deposited at the end  
of the OLED that is distal to the substrate.

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"Hole-injection layer," as used herein, is a layer into which holes are injected  
from an anode when a voltage is applied across an OLED.

"Hole-transport layer," as used herein, is a layer having high hole mobility and  
high affinity for holes that is between the anode and the emitter layer. It will be  
evident to those of skill in the art that the hole-injection layer and the hole-transport

layer can be a single layer ("hole-injection/hole-transport layer"), or they can be distinct layers comprising different chemical compounds.

"Electron-injection layer," as used herein, is a layer into which electrons are injected from a cathode when a voltage is applied across an OLED.

5 "Electron-transport layer," as used herein, is a layer having high electron mobility and high affinity for electrons that is between the cathode and the emitter layer. It will be evident to those of skill in the art that the electron-injection layer and the electron-transport layer can be a single layer ("electron-injection/electron-transport layer"), or they can be distinct layers comprising different chemical

10 compounds.

"Down-emitting," as used herein, refers to an OLED in which light is transmitted through the transparent or semi-transparent bottom electrode, which is typically an anode.

"Up-emitting," as used herein, refers to an OLED in which light is transmitted through the transparent or semi-transparent top electrode, which is typically a cathode.

15 High energy (*i.e.*, blue) light in full-color OLED display devices may be produced by any source, but is preferably produced by an emissive monochromatic OLED display device, such as the one shown in Figure 1 and described below. The 20 monochromatic OLED display device may or may not be pixelated. Preferably the OLED display is pixelated and is of high resolution, for example, with sub-pixel sizes less than about 50  $\mu\text{m}$ , preferably less than about 25  $\mu\text{m}$ , more preferably less than about 10  $\mu\text{m}$ .

25 The device of Figure 1 comprises a substrate 101, which can be transparent or opaque (and which may further comprise driving electronics), a patterned bottom electrode 102, which is a cathode or an anode, a first charge transport layer 103, which is a hole-transport layer if the bottom electrode is an anode and which is an electron-transport layer if the bottom electrode is a cathode, an emitter layer 104, a 30 second transport layer 105, which is a hole-transport layer if the bottom electrode is a cathode and which is an electron-transport layer if the bottom electrode is an anode, a top electrode 106, which is a cathode if the bottom electrode is an anode and which is an anode if the bottom electrode is a cathode, and which may be patterned (*i.e.*, in passive matrix displays) and a protective layer 107. Each element of the patterned bottom electrode 102 represents one pixel in the matrix. When current is applied to

the elements of the patterned bottom electrode 102, holes are transported through the hole-transport layer 103 or 105 and electrons are transported through the electron-transport layer 105 or 103 and holes and electrons recombine in the light emitting layer 104 to produce light of the same wavelength 108, e.g., blue light, at each pixel.

5 "Patterning," as used herein, means that the materials are formed into stripes, squares, rectangles, triangles, hexagons, circles, or any other shape known in the art. Preferably, each individual OLED is rectangular and the color changing materials are patterned in parallel stripes, or rectangular dots. The patterning of color changing materials provides for the formation of discrete red, green and blue sub-pixels, without having the colors mix together.

10 Electrodes can be patterned by any method known in the art, including, but not limited to lithographic, particularly photolithographic techniques, laser ablation, and masking during deposition.

15 A full-color OLED display device is shown in Figure 2, and comprises the elements of a monochromatic display device, including a substrate 101, which can be transparent or opaque (and which may further comprise driving electronics), a patterned bottom electrode 102, which is a cathode or an anode, a first charge transport layer 103, which is a hole-transport layer if the bottom electrode is an anode and which is an electron-transport layer if the bottom electrode is a cathode, an 20 emitter layer 104, a second charge transport layer 105, which is a hole-transport layer if the bottom electrode is a cathode and which is an electron-transport layer if the bottom electrode is an anode, a top electrode 106, which is a cathode if the bottom electrode is an anode and which is an anode if the bottom electrode is a cathode, and a first protective layer 107 covering the cathode 106. The full-color OLED display 25 device further comprises a first color changing layer 209 comprising a first patterned color changing material 210, a second protective layer 207 covering the first color changing layer 209, a second color changing layer 211 comprising a second patterned color changing material 212 adjacent to the second protective layer 207, and an encapsulation layer 207 covering the second color changing layer 211.

30 The matrix of pixels 215, each comprising a red, a green and a blue sub-pixel, in a full-color OLED display device shown in Figure 2 may be formed as follows. Each element of the patterned electrode 102 represents one sub-pixel in the matrix. A first patterned color changing material 210 is aligned with a first element of the patterned bottom electrode 102 so that the first patterned color changing material is

directly above a specified element 102. In a similar fashion, the second patterned color changing material 212 is aligned with a second element of the patterned bottom electrode 102 adjacent to the first element. A third element of the patterned bottom electrode 102 adjacent to the second element is not aligned with a patterned color changing material. When a current is applied between the top electrode 106 and the patterned bottom electrode 102, holes are transported through the hole-transport layer 103 or 105 and electrons are transported through the electron-transport layer 105 or 103 and holes and electrons recombine in the emitter layer 104 to produce light of a particular wavelength 208, e.g., blue light, at each sub-pixel. For a green sub-pixel, when blue light is emitted from the emitter layer 104 at the first element of the patterned electrode 102, it is absorbed by the first patterned color changing material 210 ("blue-to-green CCM") that is aligned with the first element. The first patterned color changing material 210 then emits green light 213 by fluorescence or phosphorescence. For a red sub-pixel, when blue light is emitted from the emitter layer 104 at the second element of the patterned bottom electrode 102, it is absorbed by the second patterned color changing material 212 ("blue-to-red CCM") that is aligned with the second element. The second patterned color changing material 212 then emits red light 214 by fluorescence or phosphorescence. For a blue sub-pixel, when blue light is emitted by the emitter layer 104 at the third element of the patterned bottom electrode 102, the blue light 208 is transmitted through the various layers 207, 209 and 211 substantially without being absorbed. The patterning of the first and second color changing materials are repeated every fourth element, resulting in an array of pixels 215 each comprising a red, a green and a blue sub-pixel.

An embodiment of a down-emitting full-color OLED display device, shown in Figure 3, comprises a first color changing layer 309 comprising a first patterned color changing material 310 deposited on a substrate 301, a first protective layer 307 covering the first color changing layer 309 formed on a transparent or semi-transparent substrate 301. A second color changing layer 311 comprises a second patterned color changing material 312 adjacent to the first protective layer 307, a second protective layer 307 covering the second color changing layer 311, a patterned bottom electrode 302, which is a cathode or an anode, a first charge transport layer 303, which is a hole-transport layer if the bottom electrode is an anode and which is an electron-transport layer if the bottom electrode is a cathode, an emitter layer 304, a second charge transport layer 305, which is a hole-transport layer if the bottom

electrode is a cathode and which is an electron-transport layer if the bottom electrode is an anode, a top electrode 306, which is a cathode if the bottom electrode is an anode and which is an anode if the bottom electrode is a cathode, and an encapsulation layer 307.

5        In this embodiment, for a red sub-pixel, blue light 308 is emitted downward from the emitter layer 304 at the first element of the patterned bottom electrode 302, and is absorbed by the first patterned color changing material 310 ("blue-to-red CCM") that is aligned with the first element. The first patterned color changing material 310 then emits red light 313 by fluorescence or phosphorescence. For a green sub-pixel, when blue light is emitted from the emitter layer 304 at the second element of the patterned bottom electrode 302, it is absorbed by the second patterned color changing material 312 ("blue-to-green CCM") that is aligned with the second element. The second patterned color changing material 312 then emits green light 314 by fluorescence or phosphorescence. For a blue sub-pixel, when blue light is emitted by the emitter layer 304 at the third element of the patterned bottom electrode 10 302, the blue light 308 is transmitted through the various layers 307, 309 and 311 substantially without being absorbed. The patterning of the first and second color changing materials are repeated every fourth element, resulting in an array of pixels 15 315 each comprising a red, a green and a blue sub-pixel.

20        OLEDs can be fabricated by any method known in the art. The OLED layers may be formed by evaporation, spin casting, self-assembly or other appropriate film-forming techniques. Thicknesses of the layers typically range from a few monolayers to about 2,000 Angstroms. In one embodiment, OLEDs are formed by vapor deposition of each layer. In a preferred embodiment, OLEDs are formed by thermal 25  vacuum vapor deposition.

30        The OLEDs described in Figures 2 and 3 are by way of example, and any type can be used. For example, an OLED may comprise a hole-injection layer adjacent to the anode and at least two hole-transport layers, a first hole-transport layer adjacent to the hole-injection layer and a second hole-transport layer adjacent to the first hole-transport layer. The hole-injection layer and the at least two hole-transport layers may be deposited separately. Alternately, at least two of the layers may be inter-deposited.

      An OLED may comprise an electron-injection layer and at least one electron-transport layer, or the OLED can further comprise an additional layer adjacent to the top electrode. In a preferred embodiment, the layer comprises indium tin oxide.

Other OLED structures will be evident to those skilled in the art.

A substrate may be made from any material known in the art, including glass, silicon, plastic, quartz and sapphire. If the OLED display is formed on a silicon chip, the chip preferably includes drive electronics and one of the sub-pixel electrodes. The 5 top electrode may be common to all sub-pixels.

An anode is typically about 800 Å thick and can have one layer comprising a metal having a high work function, a metal oxide and mixtures thereof. Preferably, the anode comprises a material selected from the group consisting of a conducting or semiconducting metal oxide or mixed metal oxide such as indium zinc tin oxide, 10 indium zinc oxide, ruthenium dioxide, molybdenum oxide, nickel oxide or indium tin oxide, a metal having a high work function, such as gold or platinum, and a mixture of a metal oxide and a metal having a high work function. In one embodiment, the anode further comprises a thin layer (approximately 5-15 Å thick) of dielectric material between the anode and the first hole-injection/hole-transport layer. 15 Examples of such dielectric materials include, but are not limited to, lithium fluoride, cesium fluoride, silicon oxide and silicon dioxide. In another embodiment, the anode comprises a thin layer of an organic conducting material adjacent to the hole-injection/hole-transport layer. Such organic conducting materials include, but are not limited to, polyaniline, PEDOT-PSS, and a conducting or semi-conducting organic 20 salt thereof.

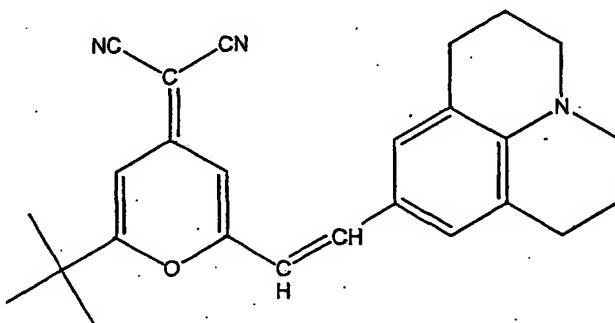
A semi-transparent cathode, such as used in Figure 2, is typically between 70 and 150 Å thick. In one embodiment, the cathode comprises a single layer of one or more metals, at least one of which has a low work function. Such metals include, but are not limited to, lithium, aluminum, magnesium, calcium, samarium, cesium and mixtures thereof. Preferably, the low work function metal is mixed with a binder 25 metal, such as silver or indium. In another embodiment, the cathode further comprises a layer of dielectric material adjacent to the electron-injection/electron-transport layer, the dielectric material including, but not limited to, lithium fluoride, cesium fluoride, lithium chloride and cesium chloride. Preferably, the dielectric 30 material is lithium fluoride or cesium fluoride. In preferred embodiments, the cathode comprises either aluminum and lithium fluoride, a mixture of magnesium and silver, a mixture of lithium and aluminum, or calcium followed by aluminum. In yet another embodiment, the cathode comprises magnesium, silver and lithium fluoride.

In one embodiment, the hole-injection/hole-transport layer is about 750 Å thick. Hole-injection/hole-transport layers typically comprise at least one material with good hole mobility. Examples of such materials include, but are not limited to, copper phthalocyanine (CuPc), and aromatic amine compounds such as N,N'-bis(1-naphthyl)-N,N'-diphenyl-1,1'-biphenyl-4,4'-diamine (NPD), bis(N,N'-1-naphthyl-phenyl-amino-biphenyl)-biphenyl amine (BPA-DNPB) and bis(carbazol-N-biphenyl)-biphenyl amine (BPA-BCA).

An OLED may further comprise an emitter layer between the electron-injection/electron-transport layer and the hole-injection/hole-transport layer in which electrons from the electron-injection/electron-transport layer and holes from the hole-injecting/hole-transport layer recombine. Depending on the composition of the emitter layer, OLEDs emit visible light of different colors. Emitter layers typically comprise at least one host compound, either alone or together with at least one dopant compound, which is a luminophor. Examples of host compounds include, but are not limited to, 2,2',7,7'-naphthyl-9,9'-spirobifluorene (N-SBF), ALQ, IDE-120 and IDE-140 (Idemitsu Kosan Co., Ltd., Tokyo, Japan). Examples of dopant compounds include, but are not limited to, Coumarin 6, Coumarin 485, Coumarin 487, Coumarin 490, Coumarin 498, Coumarin 500, Coumarin 503, Coumarin 504, Coumarin 504T, Coumarin 510, Coumarin 515, Coumarin 519, Coumarin 521, Coumarin 521T, Coumarin 522B, Coumarin 523, Coumarin 525, Coumarin 535, Coumarin 540A, Coumarin 545, Coumarin 545T, quinacridone derivatives such as diethyl pentyl quinacridone and dimethyl quinacridone, distyrylamine derivatives, such as IDE-102, IDE-105 (Idemitsu Kosan Co., Ltd., Tokyo, Japan), rubrene, DCJTB, pyrromethane 546, and mixtures thereof. The structure of DCJTB is shown below:

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In one embodiment, the emitter layer emits white or blue light and comprises DCJTB, IDE-102 and IDE-120.

The emitter layer may be between 200-400 Å thick.

5 The electron-injection/electron-transport layer is typically about 350 Å thick and comprises a compound such as ALQ, or a suitable oxadiazole derivative. In a preferred embodiment, the electron-injection/electron-transport layer is N-SBF, ALQ, or a mixture of N-SBF and ALQ.

10 In one embodiment, a blue-emitting OLED for use in color OLED displays comprises an anode comprising indium tin oxide, a hole-injection layer adjacent to the anode comprising CuPc, a hole-transport layer adjacent to the hole-injection layer comprising NPD, an emitter layer adjacent to the hole-transport layer comprising DCJTB, IDE-102 and IDE-120, an electron-transport layer adjacent to the emitter layer comprising ALQ, and a cathode comprising lithium fluoride and aluminum.

15 A method for forming patterned color changing materials on or under an OLED display device will now be described. The first step in the process is shown in Figure 4. In this step, a blue-to-green CCM layer 401, for example, is deposited on the protective layer 107 of an up-emitting monochromatic OLED display device, such as shown in Figure 1. In the case of a down-emitting device such as shown in Figure 3, the layer 401 would be deposited on the substrate 307. CCM layers can be 20 deposited by any method known in the art, including spin-coating, meniscus-coating, spray-coating, dip-coating, blade-coating, from solution or suspension or by sublimation in a vacuum.

25 In a second step, shown in Figure 5, a photomask 501 is placed over the CCM layer 401 such that the light absorbing areas (i.e., areas that block light) 502 are aligned with every fourth electrode element 102 that will be green sub-pixels. Light 503, preferably ultraviolet light, in an ambient atmosphere is shone through the photomask 501 to photo-oxidize the exposed areas of layer 401, causing them to become transparent. The photomask 501 is transparent to the light 503 everywhere except in the light absorbing areas 502. As shown in Figure 6, the blue-to-green 30 CCM layer is photobleached in the areas 601 where the photomask is transparent to the light, while the areas masked by the light absorbing areas of the photomask comprise unbleached blue-to-green CCMs 602. A protective layer 603 is then deposited on the patterned blue-to-green CCM 601, 602. Preferably, light having a wavelength of between about 250 nm and 420 nm, more preferably between about

300 nm and 400 nm and most preferably between about 330 nm and 380 nm is used for the photo-oxidation. The source of the light can be a laser, a mercury lamp, a xenon lamp, or any other intense source of light and preferably of ultraviolet light.

The process is repeated for patterning the blue-to-red CCM to create red sub-pixels. As shown in Figure 7, a blue-to-red CCM layer 701 is deposited on the protective layer 603 that is deposited on the patterned blue-to-green CCM layer 601, 602. Figure 8 shows the next step, where a photomask 801 is placed over the blue-to-red CCM layer 701 such that the light absorbing areas 802 are shifted over one electrode element and are aligned with every fourth electrode element 102 that will be red sub-pixels. Light, preferably ultraviolet light, in an ambient atmosphere 803 is shone through the photomask 801. The photomask 801 is transparent to the light 803 everywhere except in the light absorbing areas 802. The results of photo-oxidation of the blue-to-red CCM layer 701 is shown in Figure 9. The blue-to-red CCM layer is photobleached in the areas 901 where the photomask is transparent to the light, while the areas masked by the light absorbing areas of the photomask comprise unbleached blue-to-red CCMs 902. The blue-to-green CCMs 602 will not be photo-oxidized during this process because the protective layer 603, which absorbs the light used in the photo-oxidation process and because substantially no oxygen will penetrate into the CCM layer 602 after encapsulation.

Preferably, the CCM layers are encapsulated and protected from photo-oxidation after the deposition and patterning steps of all CCM layers are finished, e.g. by a pin-hole free dielectric layer 903, deposited on the patterned blue-to-red CCM layer 901, 902. No CCM is placed over the third electrode element 102. When a voltage is applied, the monochromatic OLED display emits blue light 904, which is either transmitted through the protective layers 107, 603, 903 and the bleached CCM layers 601, 901 at a blue sub-pixel 905 or is absorbed by the patterned blue-to-green CCM 602 or by the patterned blue-to-red CCM 902, which in turn emit green or red light, respectively, to form a green sub-pixel 906 and a red sub-pixel 907, respectively. Thus, a full-color OLED display device is formed.

"Photobleached" or "photo-oxidized," as used herein, means that a material becomes substantially transparent to visible light and that its photoluminescence is substantially eradicated upon exposure to, e.g., ultraviolet light and oxygen. Preferably, the photobleached parts of the CCM layers have blue-shifted absorption and transmit more than 90% of the light emitted by the monochromatic OLED

display, and have remaining absolute quantum efficiency of photoluminescence of less than about 5 %, preferably less than about 1 %. Preferably, photo-oxidized areas transmit substantially all of the light having a wavelength between about 440 nm and 520 nm, more preferably between about 420 nm and 650 nm, and most preferably 5 between about 400 nm and 750 nm.

- An additional embodiment of a full-color OLED display device is shown in Figure 10. In this embodiment, a filter layer 1001 that comprises a blue optical filter 1002 over each blue sub-pixel 905 is deposited on the third protective layer 903. The color filters can be patterned or unpatterned and purify the emission spectrum.
- 10 Although a blue optical filter is pictured in Figure 10, it will be understood by one of skill in the art that color filters may be used with emission from the other sub-pixels, as well.

One of skill in the art will readily appreciate that, although this process is illustrated herein for an up-emitting OLED display device, it can be used to create 15 patterned CCM layers in a down-emitting device, such as that shown in Figure 3. One of skill in the art will further appreciate that, although the method of the present invention has been illustrated herein with a green CCM deposited in a layer closer to the monochromatic OLED display device and a red CCM deposited in a layer further away, the layers can be interchanged.

20 In addition, although the method of the present invention has been illustrated for generating red and green sub-pixels, one of skill in the art will recognize that sub-pixels of any color can be generated simply by altering the color changing materials. For example, only one CCM layer can be used on a monochromatic OLED display device. Alternatively, many CCM layers can be used and the CCM emission colors 25 may vary, e.g., one could have a monochromatic OLED display that emits deep blue light in combination with CCM films patterned as described herein that emit, for example, yellow/green and orange light. Preferably, the monochromatic OLED display device emits blue light (close to CIE (0.155; 0.07)) and there are two CCM layers, one emitting red light (close to CIE (0.625; 0.34)) and the other emitting green 30 light (close to CIE (0.28; 0.595)) to form a proper red-green-blue ("RGB") display.

The photo-oxidation may be done using a standard ultraviolet mask-aligner or exposure tool or similar devices capable of achieving the desired resolution. Mask aligners can easily achieve the preferred 1 - 5  $\mu$ m resolution. The wavelength of radiation used to photo-oxidize, e.g., the green CCM layer, in the presence of oxygen

should at least partly overlap with the absorption spectrum of the green CCM (or at least of one of the components thereof) and should be capable of photobleaching the CCM layer in the desired manner described in the invention. Therefore, where the CCM layer is exposed to radiation in the presence of oxygen, the photoluminescence of the material will be reduced and the absorption band of the material will blue-shift, with the result that the photo-oxidized CCM becomes more transparent to visible light (i.e., only absorbing light of higher energy, such as ultraviolet light). Thus, only those areas of the film not exposed to the light and oxygen will remain green-luminescent, and the other areas will be transparent to visible light and without photoluminescence, as shown in Figure 9.

The wavelength of light used in the methods of the present invention, which is preferably deep blue or ultraviolet light (preferably having a wavelength of between about 330 nm and 380 nm), is preferably optimized to the absorption of the color changing materials, e.g., by using excitation color filters to "tune" the wavelength of light. Preferably, the wavelength of light used to photo-oxidize the CCMs is absorbed in the underlying substrate in order to avoid wave-guiding and scattering that may reduce resolution and accuracy of the patterning process described herein.

Exposure time is also preferably optimized in order to achieve good transparency of the photo-oxidized portions of the CCM to blue light emitted from the underlying monochromatic OLED display, as well as to achieve low photoluminescence in the exposed areas. Standard mask aligners normally allow light of sufficient intensity to penetrate through to the CCM so that CCM patterning can be achieved in a few minutes. Preferably, the time for photo-oxidation is between about 1 min. and 10 min., more preferably between about 1 min. and 3 min.

The CCM layers may further comprise chemicals such that, when the CCM is exposed to light, the exposed area is properly photobleached in the absence of oxygen. Thus, the patterning can be done, e.g., in a dry and oxygen-free glove box, which may be useful if the CCMs are deposited and patterned directly on top of the an OLED. Alternatively, the CCM layers may be exposed in the absence of water or oxygen to high-intensity ultraviolet light, which requires the use of highly stable CCMs.

When CCMs are deposited on a substrate (as shown in Figure 3), they may be deposited and patterned on a variety of substrates, including, but not limited to, glass, plastic, quartz, and sapphire. CCMs may be deposited and patterned as described in

the present invention on the OLED itself, such as when the OLED is first deposited on the substrate and the CCMs are deposited on top, as shown in Figure 2. CCMs may alternatively be deposited on the substrate and patterned, and then the OLED may be deposited on the CCMs, as shown in Figure 3. Preferably, the CCM layers are

5 deposited on top of the OLED. In one configuration, shown in Figure 11, in an up-emitting OLED display device, there is no protective layer between the top electrode and the first CCM layer. Thus, the blue OLED stack 1102 is deposited on the substrate 1101; one or more patterned CCM layers and protective layers 1103 are deposited directly onto the OLED stack 1102. An encapsulation layer 1104 is

10 deposited on the one or more CCM layers and protective layers 1103. Preferably, there is a protective layer between the OLED stack and the alternating CCM layers and protective layers.

In another configuration, shown in Figure 12, in a down-emitting OLED display device, the one or more CCM layers and protective layers 1202 are deposited

15 directly onto a transparent substrate 1201; the OLED stack 1203 is then deposited onto the one or more CCM layers and protective layers 1202 and an encapsulation layer 1204 is deposited on the OLED stack.

In yet another configuration, shown in Figure 13, in a down-emitting OLED display device, the one or more CCM layers and protective layers 1302 are deposited

20 on a first encapsulation layer 1301. A transparent substrate 1303 is then deposited on the one or more CCM layers and protective layers 1302. An OLED stack 1304 is deposited on the transparent substrate 1303, and a second encapsulation layer 1305 is deposited on the OLED stack 1304.

In another configuration, shown in Figure 14, one or more CCM and protective layers 1402 may be deposited and patterned as described in the invention

25 on a separate transparent substrate 1401 (e.g., a glass slide also used to encapsulate the OLED display) which is subsequently aligned on and then laminated or bonded or glued 1403 to an OLED stack 1404 that is deposited on a substrate 1405. Such a configuration may also serve to encapsulate the OLED display. If there is more than

30 one CCM layer to be patterned as described above, all CCM layers may be deposited on one and the same substrate (on top of each other with alternating protective layers), or on different substrates, in which case protective layers may not be needed.

If multiple CCM or filter layers are deposited on a single substrate and sequentially on top of each other, then a protective layer is deposited over each

patterned layer. The protective layer preferably comprises inert materials that are transparent and have low or no luminescence. The protective layer is preferably not patterned. Without being bound by any theory, the protective layer absorbs the radiation used in the patterning method and/or prevents ambient oxygen from 5 penetrating to the lower layers in order to prevent the already-patterned underlying layers from being re-exposed.

Suitable materials for the protective layer are preferably able to absorb light used in the methods of the present invention (usually ultraviolet light), are able to block oxygen penetration into the other layers, are transparent to visible light (usually 10 red, green and blue), are non-fluorescent and are easily deposited onto the CCM layers without harming them. Preferably, such materials are deposited onto the CCM layers by heat or e-beam evaporation or are sputtered (reactive DC or RF). Suitable protective layer materials are known in the art and include, but are not limited to, metal oxides such as  $\text{SiO}_2$ ,  $\text{SiN}$ ,  $\text{MgO}$ , and  $\text{ITO}$ , organic polymers, conjugated 15 polymers, additives such as benzophenones, heat and/or ultraviolet curing epoxy compounds, spin-on-glass materials, siloxanes and combinations thereof. If the protective layer material is fluorescent, it may be quenched by, e.g., photo-oxidation if photoluminescent quenchers such as metals, ions, dopants or other impurities are added to the material.

20 A protective layer may also be used on a substrate if, for example, the optimum wavelength of light for patterning is in a range where the substrate does not absorb. For example, glass strongly absorbs light of wavelength below 330 nm. Therefore, if a glass substrate is used with a wavelength of light for patterning the CCM layers (particularly when the first CCM layer is on the substrate) that is above 25 330 nm, then the light may penetrate the substrate and be waveguided and/or scattered. This in turn could result in a partial or even complete photo-oxidation of those parts of the CCM film that not to be photo-oxidized. In this case it may be preferable to cover the substrate with a protective layer in order to avoid waveguiding and/or scattering effects. Alternatively, special glass or other substrate materials may 30 be used that strongly absorb the wavelength of light used for patterning. Examples of such materials include colored glass, such as Schott glass filters.

Color changing materials may comprise any material known in the art. For example, CCM layers may comprise compounds including, but not limited to, pure sublimed luminophors (such as those used in the emitter layers of OLEDs), sublimed

host molecules (luminophors) that are doped (co-evaporated) with other materials in order to improve quantum efficiency of photoluminescence, purely organic or organometallic materials, or unconjugated, conjugated or partially conjugated polymers or co-polymers.

5 If a CCM is a doped layer, the host can be chosen to optimize its absorption of the wavelength of light emitted by the monochromatic OLED display (usually blue light), and the dopant can be chosen to emit the desired wavelength of light (usually red or green light).

An example of a host compound is ALQ. Examples of dopant compounds  
10 include, but are not limited to, Coumarin 6, Coumarin 485, Coumarin, 487, Coumarin 490, Coumarin 498, Coumarin 500, Coumarin 503, Coumarin 504, Coumarin 504T, Coumarin 510, Coumarin 515, Coumarin 519, Coumarin 521, Coumarin 521T, Coumarin 522B, Coumarin 523, Coumarin 525, Coumarin 535, Coumarin 540A, Coumarin 545, Coumarin 545T, quinacridone derivatives such as diethyl pentyl  
15 quinacridone and dimethyl quinacridone, distyrylamine derivatives, such as IDE-102, IDE-105 (Idemitsu Kosan Co., Ltd., Tokyo, Japan), rubrene, DCJTB, pyrromethane 546, and mixtures thereof.

Color changing materials can also comprise pure polymers or polymer blends, fluorescent polymers or luminophors doped into conjugated or partly conjugated  
20 fluorescent or nonfluorescent polymers. A wide range of polymers and copolymers are available as CCMs because different side groups can be attached to a particular backbone. In addition, co-polymers can be used. Examples of useful polymers in CCMs are known in the art and include, but are not limited to, PPV polymers, thiophene-based polymers, inert polymers with attached luminophor side groups, 25 fluorene-based polymers, phenylene-based polymers, furylene-based polymers, oligomers, oligomers with spiro centers, and combinations and co-polymers thereof.

Preferred CCMs are doped materials, polymer blends and copolymers.

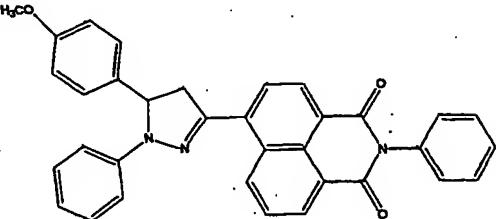
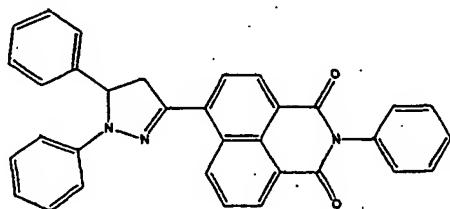
In general, CCM materials for use in the methods of the present invention are preferably rendered non-luminescent (or have very low luminescence) and are  
30 substantially transparent to visible light when photo-oxidized. In particular, CCM materials for use in the methods of the present invention can be patterned without removing any material from the CCM layer. If guest/host CCM films are used then at least one but preferably both of the two (or more) components are rendered inactive, i.e., they do not absorb visible light and do not emit light by photoluminescence. This

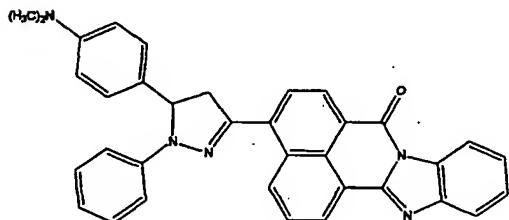
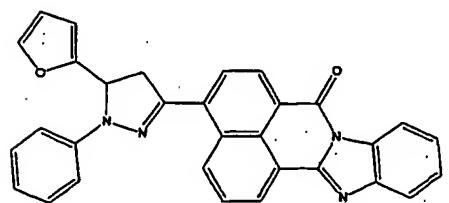
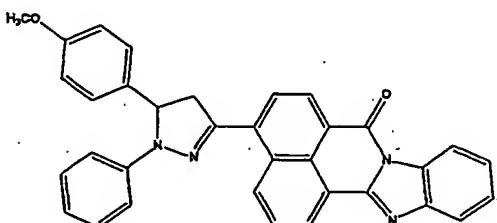
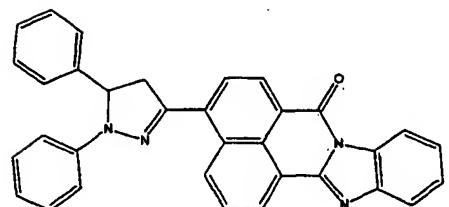
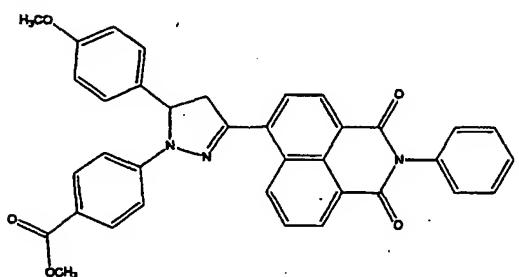
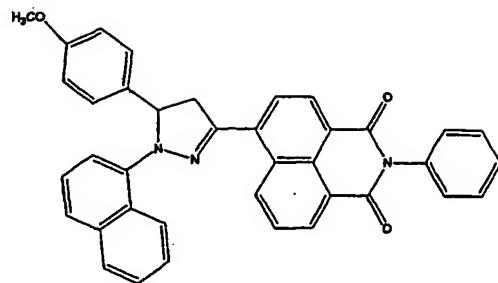
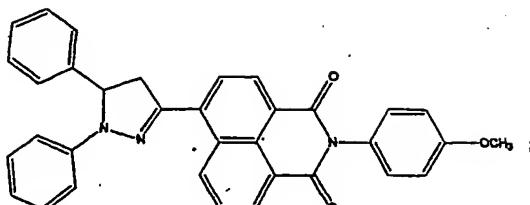
can be achieved by either shifting the absorption to higher energy (blue-shift) so that the CCM does not absorb the light emitted from the monochromatic OLED display and/or by quenching photoluminescence so that the CCM film, where photo-oxidized, has at least partly but preferably strongly reduced PL upon excitation with light emitted from the monochromatic OLED display.

CCMs that emit red or green light preferably have an absolute quantum efficiency of photoluminescence that is greater than about 50%, preferably greater than about 70%, and more preferably greater than about 80%. Such efficiencies are preferably achieved by multi-component color changing materials, wherein the major component (comprising about 90-98% of the material) absorbs blue light efficiently, the minor component (dopant) has high quantum efficiency of photoluminescence in the desired wavelength range, and there is efficient energy transfer from the major component to the dopant.

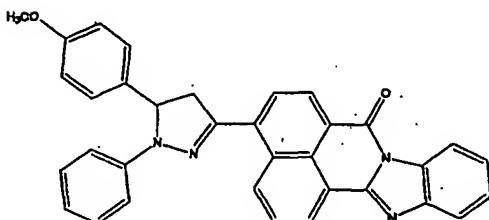
For example, a blue-to-green CCM may be Coumarin 540-doped ALQ and a blue-to-red CCM may be DCJT-doped ALQ. In another embodiment, a blue-to red CCM is a PPV copolymer with cyano- groups attached to the vinyl groups of the polymer backbone or a poly-alkyl-thiophene polymer, and a blue-to-green CCM is a polyfluorene-based copolymer, a PPV polymer with discontinuous conjugation (i.e., with electrically and optically inert spacer groups) or a PPV polymer with solubilising side groups, such as a di-alkyl PPV.

Particularly preferred blue-to-red CCM materials include, but are not limited to:

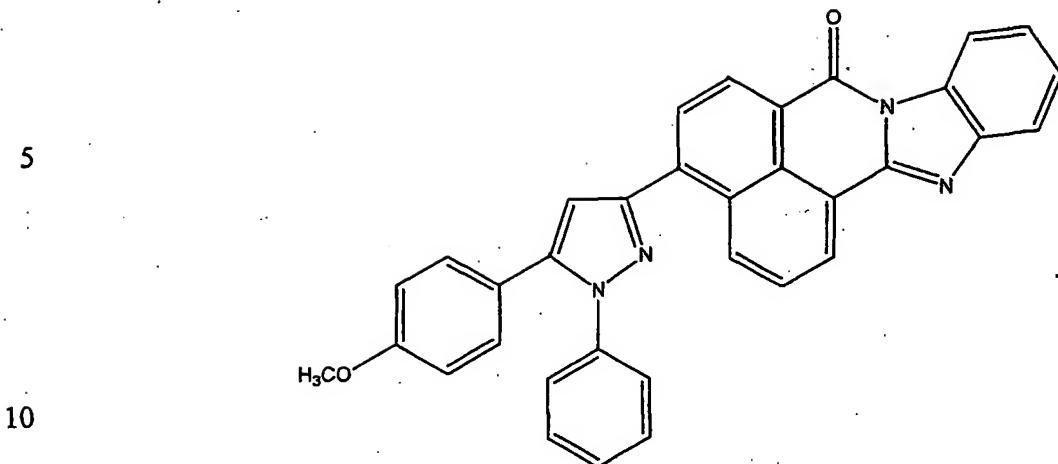




; and



A particularly preferred blue-to-green CCM has the formula:



CCM layers are preferably less than about 3  $\mu\text{m}$  thick, more preferably less than about 2  $\mu\text{m}$  thick, and most preferably less than about 1  $\mu\text{m}$  thick. As the thickness of the CCM layers increases, the layers may waveguide or scatter the light they emit, which in turn may lead to loss of brightness and contrast in the displays. Color changing materials preferably have optical densities for the excitation and patterning light sources of greater than about 1, more preferably between about 2 - 4 (i.e., transmission of about 0.01% to about 1%) and most preferably between about 2-3. If the optical density of the CCMs are further increased in order to absorb more light from the monochromatic OLED display, some of the green or red photoluminescence from the materials may be re-absorbed in the CCM layers, thus reducing the brightness of the display.

## EXAMPLES

25      EXAMPLE 1: OPTIMIZATION OF CCM PATTERNING BY PHOTO-OXIDATION

In a first step, referred to Figure 15, a glass substrate 1501 is carefully cleaned and a thin film of a standard green emitter, ALQ and a dye, such as Coumarin 540 1502 is evaporated thereon. The substrate must be very clean and free of water. The 30 initial thickness of the evaporated layer 1502 is about 200 nm.

In a second step, the absorption spectrum of the film 1502 deposited in step 1 is measured and compared with the emission spectrum of a blue-emitting OLED. For example, a good CCM candidate absorbs about 95 % of the blue light from the underlying OLED. If this is not the case, then the thickness of the film 1502 may be

increased until about 95% of the blue light is absorbed. Alternatively, the host material in the green film can be changed to one that absorbs the light more efficiently. The sufficiency of absorption of the blue emission can be checked by placing the green film over a blue-emitting device and measuring how much of the 5 blue light is transmitted (with reference to the amount of light emitted by the blue-emitting OLED without the film on top).

In a third step, shown in Figure 16, the green film 1602 on the substrate 1601 is exposed to ultraviolet light 1603 through a suitable photomask 1604 (pattern size of 1 mm or less) in the presence of ambient oxygen. The photo mask 1604 comprises 10 areas 1605 that are transparent to ultraviolet light and other areas 1606 that block ultraviolet light. The optimal intensity of light and time (dose) for exposure is when the areas of film 1607 that are exposed to ultraviolet light and oxygen have no or very low fluorescence and when their absorption is blue-shifted such that they become highly (ideally fully) transparent to blue light emitted from the OLED which the film 15 will cover. The areas that are not exposed to ultraviolet light 1608 should remain highly fluorescent, just as in the original film. For high-resolution patterning, the mask 1604 and substrate 1601 with the CCM film 1602 are preferably in close proximity to each other.

In order to substantially eliminate scattering of the ultraviolet light by the 20 substrate 1601, which might cause ultraviolet exposure of the areas of the film that are designed to stay intact, the wavelengths of ultraviolet light from the exposure tool used to photobleach the green film should only contain wavelengths that both overlap with the absorption spectrum of the film and are strongly absorbed into the substrate material. Thus, it may be preferable to alter the ultraviolet excitation spectrum, e.g., 25 by using band pass filters.

An alternative solution is shown in Figure 17, where a protective layer 1702 can be placed between the substrate 1701 and the green film 1703 in order to minimize scattering and waveguiding of the ultraviolet light by the substrate. The quality and performance of such patterned CCM films can easily be checked in a 30 standard fluorescence microscope.

In a final step as shown in Figure 18, the photo-patterned film 1802 is encapsulated by evaporating a film of a transparent dielectric, including but not limited to  $\text{SiO}_2$ , perylene and  $\text{Al}_2\text{O}_3$  1803 onto the film. The encapsulation layer may

also be deposited by sputtering or other methods. Alternatively, spin-on glass materials may be used for encapsulation.

5 Encapsulated films may be placed over a blue or ultraviolet light source in order to monitor the stability of the photoluminescence (intensity and spectrum) of the patterned film over time. If no protective layer is deposited on the film, then it will be prone to degradation from the environment (water, light, oxygen).

The same process can be repeated for patterning a red film comprising a red dye doped into ALQ. When the additional red CCM layer is patterned on top of the green CCM layer, then the protective layer is essential to prevent ultraviolet

10 absorption by the green film during patterning of the red film, as well as oxygen penetration to lower layers. If the green film and the red film are to be used on the same monochromatic OLED display, then the photomask pattern for the second CCM layer must be laterally shifted from the photomask pattern used to pattern the first CCM layer.

15 In a preferred embodiment, when the conditions for this process are optimized, the CCM layers are patterned directly on the OLED rather than on separate substrates, which allows for easier alignment of the patterns over the underlying OLED's electrode elements.

20

#### REFERENCES CITED

All references cited herein are incorporated herein by reference in their entirety and for all purposes to the same extent as if each individual publication or patent or patent application was specifically and individually indicated to be incorporated by reference in its entirety for all purposes as fully set forth.

25

Many modifications and variations of this invention can be made without departing from its spirit and scope, as will be apparent to those skilled in the art. The specific embodiments described herein are offered by way of example only, and the invention is to be limited only by the terms of the appended claims, along with the full scope of equivalents to which such claims are entitled.

30

## CLAIMS:

1. A method for patterning a first layer comprising a first color changing material, said method comprising:

(a) exposing at least one area of said first layer to light and oxygen and

5 leaving at least one area unexposed; and

(b) covering said at least one unexposed area with a protective layer,

wherein said first color changing material in said at least one exposed area becomes substantially transparent to visible light and substantially non-photoluminescent after said exposing step.

10

2. The method of claim 1, further comprising the steps of:

(c) forming a second layer comprising a second color changing material over said first layer; and

(d) exposing at least one area of said second layer to light and oxygen and

15 leaving at least one area unexposed,

wherein said second color changing material in said at least one exposed area becomes substantially transparent to visible light and substantially non-photoluminescent after said exposing step, and wherein said two unexposed areas are not aligned.

20

3. The method of claim 1, wherein said exposing at least one area to light is accomplished by shining said light through a photomask, wherein said photomask comprises a first area that is transparent to said light and a second area that blocks said light.

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4. The method of claim 1, wherein said at least one area has an absolute quantum efficiency of photoluminescence less than about 5% after said exposing step.

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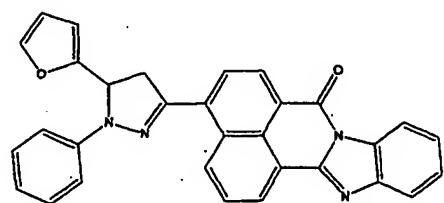
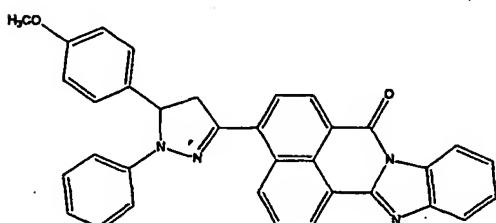
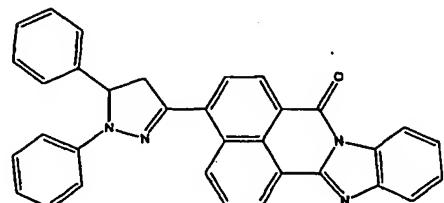
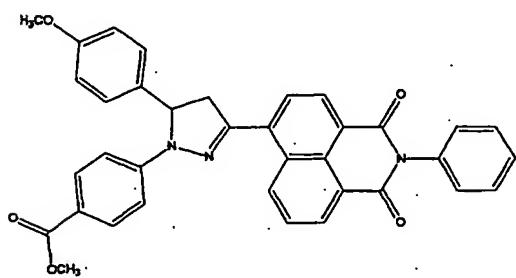
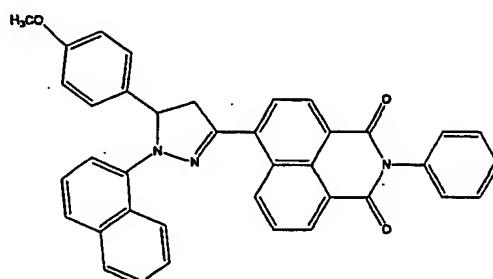
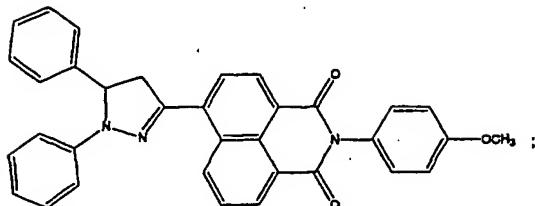
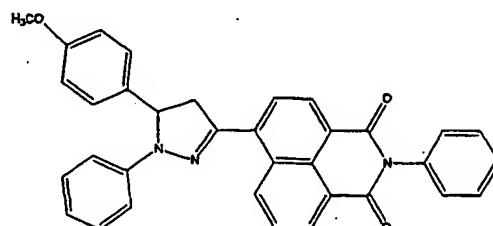
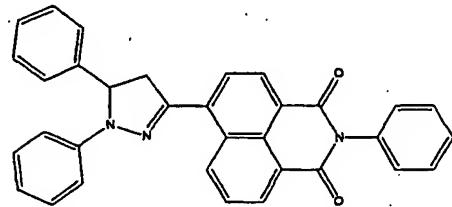
5. The method of claim 4, wherein said at least one area has an absolute quantum efficiency of photoluminescence less than about 1% after said exposing step.

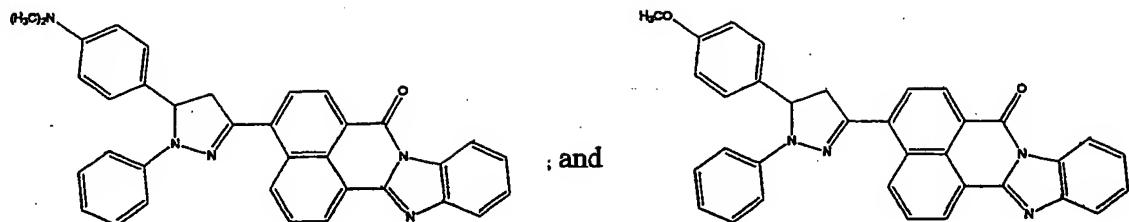
6. The method of claim 1, wherein said at least one area is substantially transparent to light having a wavelength of between about 400 nm and 750 nm after said exposing step.

7. The method of claim 1, wherein said exposing step is performed for between about 1 min. and 3 min.
- 5 8. The method of claim 1, wherein said light used in step (a) has a wavelength of between about 250 nm and 420 nm.
9. The method of claim 1, wherein said first layer is deposited on an OLED.
- 10 10. The method of claim 1, wherein said first layer is deposited on a substrate.
11. The method of claim 1, wherein said first layer is deposited on a protective layer.
- 15 12. The method of claim 11, wherein said protective layer is deposited on an OLED.
13. The method of claim 11, wherein said protective layer is deposited on a substrate.
- 20 14. The method of claim 1, wherein said first color changing material is selected from the group consisting of a PPV polymer, a thiophene-based polymer, an inert polymer with attached luminophor side groups, a fluorene-based polymer, a phenylene-based polymer, a furylene-based polymer, an oligomer with spiro centers, a co-polymer thereof and a combination thereof.
- 25 15. The method of claim 1, wherein said first color changing material comprises a host compound that is ALQ, and a dopant compound selected from the group consisting of Coumarin 6, Coumarin 485, Coumarin 487, Coumarin 490, Coumarin 498, Coumarin 500, Coumarin 503, Coumarin 504, Coumarin 504T, Coumarin 510, Coumarin 515, Coumarin 519, Coumarin 521, Coumarin 521T, Coumarin 522B, Coumarin 523, Coumarin 525, Coumarin 535, Coumarin 540A, Coumarin 545, Coumarin 545T, quinacridone derivatives such as diethyl pentyl quinacridone and

dimethyl quinacridone, IDE-102, IDE-105, rubrene, DCJTB, pyrromethane 546, and mixtures thereof.

16. The method of claim 1, wherein said first color changing material is a blue-to-red color changing material and comprises a compound selected from the group consisting of:



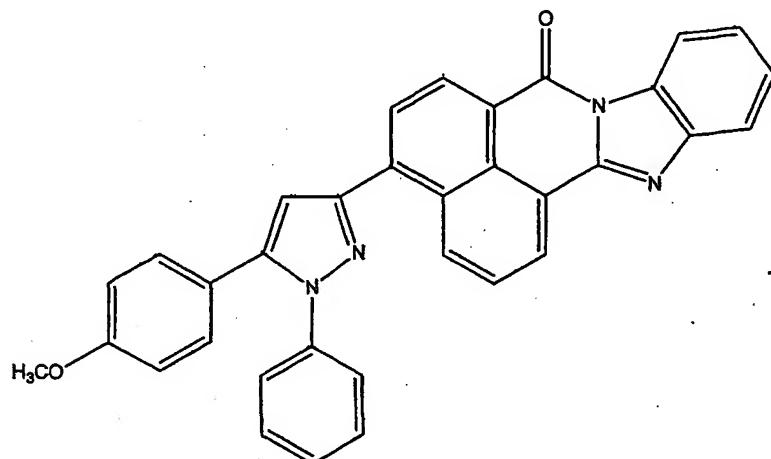


17. The method of claim 1, wherein said first color changing material is a blue-to-green color changing material and comprises the compound having the formula:

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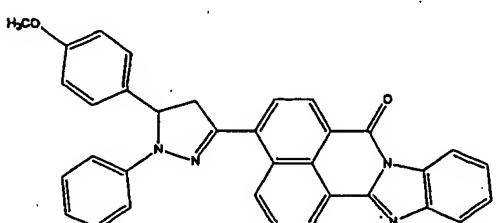
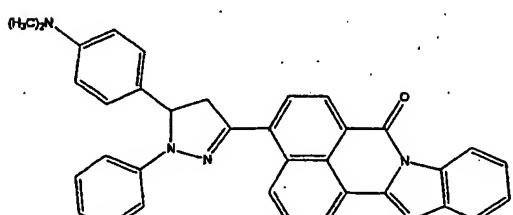
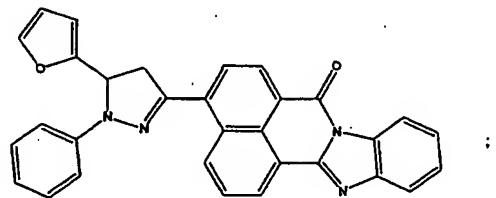
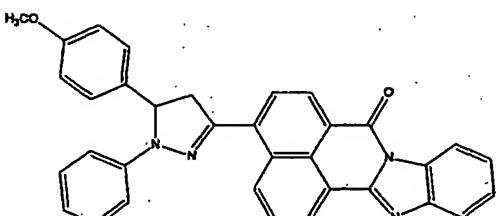
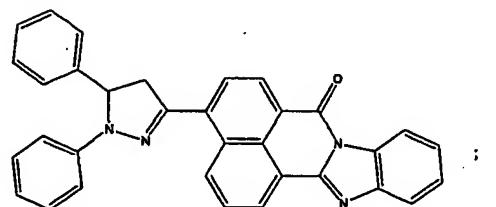
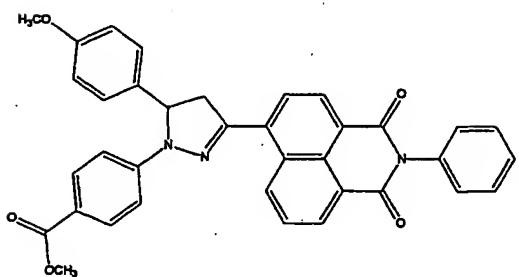
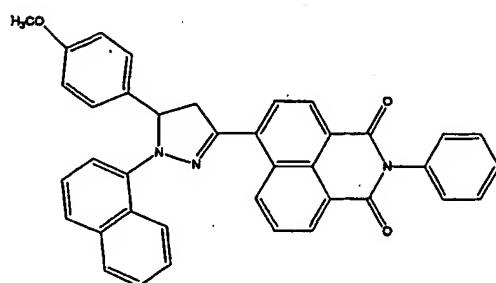
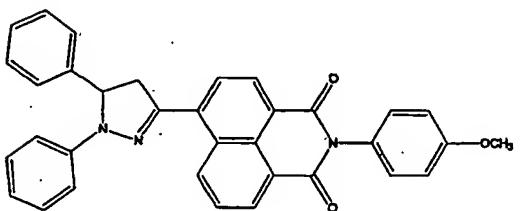
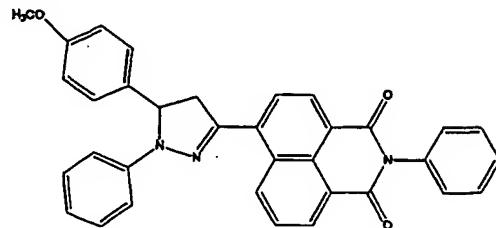
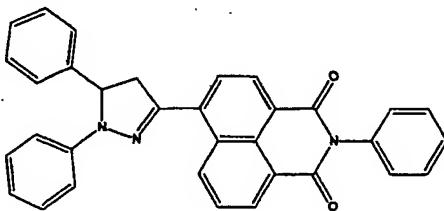


20 18. The method of claim 2, wherein said second color changing material is selected from the group consisting of a PPV polymer, a thiophene-based polymer, an inert polymer with attached luminophor side groups, a fluorene-based polymer, a phenylene-based polymer, a furylene-based polymer, an oligomer with spiro centers, a co-polymer thereof and a combination thereof.

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19. The method of claim 2, wherein said second color changing material comprises a host compound that is ALQ, and a dopant compound selected from the group consisting of Coumarin 6, Coumarin 485, Coumarin 487, Coumarin 490, Coumarin 498, Coumarin 500, Coumarin 503, Coumarin 504, Coumarin 504T, Coumarin 510, Coumarin 515, Coumarin 519, Coumarin 521, Coumarin 521T, Coumarin 522B, Coumarin 523, Coumarin 525, Coumarin 535, Coumarin 540A, Coumarin 545, Coumarin 545T, quinacridone derivatives such as diethyl pentyl quinacridone and dimethyl quinacridone, IDE-102, IDE-105, rubrene, DCJTB, pyromethane 546, and mixtures thereof.

20. The method of claim 2, wherein said second color changing material is a blue-to-red color changing material and comprises a compound selected from the group consisting of:



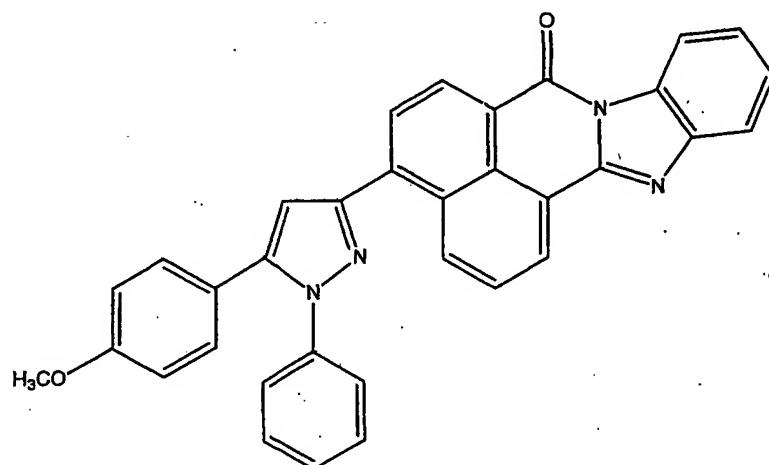
; and

21. The method of claim 2, wherein said second color changing material is a blue-to-green color changing material and comprises the compound having the formula:

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22. The method of claim 1, wherein said first layer comprising a first color changing material is less than about 3  $\mu\text{m}$  thick.

23. The method of claim 22, wherein said first layer comprising a first color changing material is less than about 2  $\mu\text{m}$  thick.

25 24. The method of claim 23, wherein said first layer comprising a first color changing material is less than about 1  $\mu\text{m}$  thick.

25. The method of claim 2, wherein said second layer comprising a second color changing material is less than about 3  $\mu\text{m}$  thick.

30 26. The method of claim 25, wherein said second layer comprising a second color changing material is less than about 2  $\mu\text{m}$  thick.

35 27. The method of claim 26, wherein said second layer comprising a second color changing material is less than about 1  $\mu\text{m}$  thick.

28. The method of claim 1, wherein said first color changing material has an optical density for ultraviolet light of greater than about 1.

29. The method of claim 28, wherein said first color changing material has an optical density for ultraviolet light of between about 2 and about 4.
30. The method of claim 29, wherein said first color changing material has an optical density for ultraviolet light of between about 2 and about 3.
- 5 31. The method of claim 2, wherein said second color changing material has an optical density for ultraviolet light of greater than about 1.
- 10 32. The method of claim 31, wherein said second color changing material has an optical density for ultraviolet light of between about 2 and about 4.
33. The method of claim 32, wherein said second color changing material has an optical density for ultraviolet light of between about 2 and about 3.
- 15 34. The method of claim 1, wherein the first color changing material in said at least one unexposed area has an absolute quantum efficiency of photoluminescence greater than about 50%.
- 20 35. The method of claim 34, wherein said first color changing material in said at least one unexposed area has an absolute quantum efficiency of photoluminescence greater than about 70%.
- 25 36. The method of claim 35, wherein said first color changing material in said at least one unexposed area has an absolute quantum efficiency of photoluminescence greater than about 80%.
- 30 37. The method of claim 2, wherein the second color changing material in said at least one unexposed area has an absolute quantum efficiency of photoluminescence greater than about 50%.
38. The method of claim 37, wherein said second color changing material in said at least one unexposed area has an absolute quantum efficiency of photoluminescence greater than about 70%.

39. The method of claim 38, wherein said second color changing material in said at least one unexposed area has an absolute quantum efficiency of photoluminescence greater than about 80%.

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40. The method of claim 1, wherein said protective layer comprises a material selected from the group consisting of  $\text{SiO}_2$ ,  $\text{SiN}$ ,  $\text{MgO}$ , ITO, an organic polymer, a conjugated polymer, a benzophenone, a heat curing epoxy compound, an ultraviolet curing epoxy compound, a spin-on-glass compound, a siloxane and a combination thereof.

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41. A method for patterning a layer comprising a color changing material, said method comprising:

- (a) aligning a photomask over said layer, said photomask comprising a first area that is transparent to light and a second area that absorbs light;
- (b) shining light through said photomask onto said layer in the presence of oxygen and leaving at least one area unexposed; and
- (c) covering said at least one unexposed area with a protective layer, wherein the area of the layer under said first area of the photomask is exposed to light and oxygen, wherein the area of the layer under said second area of the photomask is not exposed to light and oxygen,  
wherein said color changing material in said exposed area becomes substantially transparent to visible light and substantially non-photoluminescent after said exposing step, and wherein said color changing material in said unexposed area is substantially non-transparent to visible light and substantially photoluminescent after said exposing step.

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42. The method of claim 41, wherein said exposed area of said layer has an absolute quantum efficiency of photoluminescence less than about 5% after said exposing step.

43. The method of claim 42, wherein said exposed area of said layer has an absolute quantum efficiency of photoluminescence less than about 1% after said exposing step.

44. The method of claim 41, wherein said exposed area of said layer is substantially transparent to light having a wavelength of between about 400 nm and 750 nm after said exposing step.

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45. The method of claim 41, wherein said exposing step is performed for about 1 min. to 3 min.

10 46. The method of claim 41, wherein said light used in step (b) has a wavelength of between about 250 nm and 420 nm.

47. The method of claim 41, wherein said layer comprising a color changing material is deposited on an OLED.

15 48. The method of claim 41, wherein said layer comprising a color changing material is deposited on a substrate.

49. The method of claim 41, wherein said layer comprising a color changing material is deposited on a protective layer.

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50. The method of claim 49, wherein said protective layer is deposited on an OLED.

25

51. The method of claim 49, wherein said protective layer is deposited on a substrate.

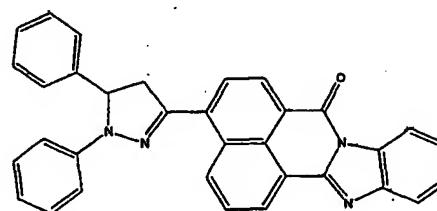
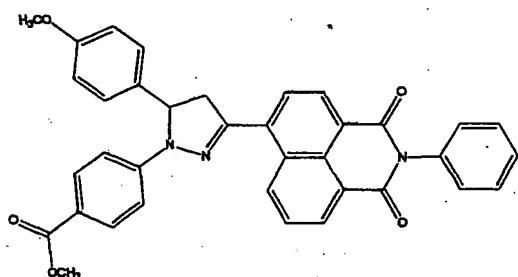
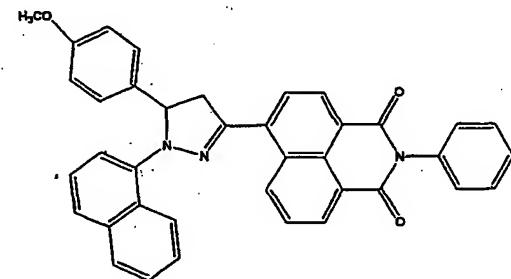
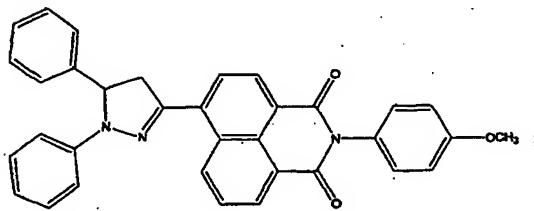
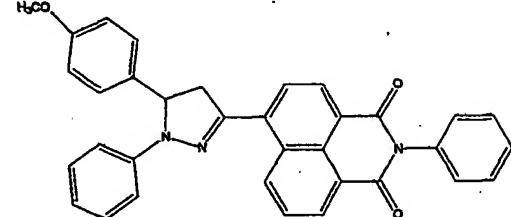
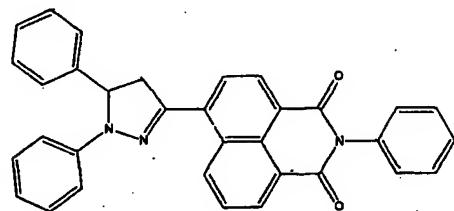
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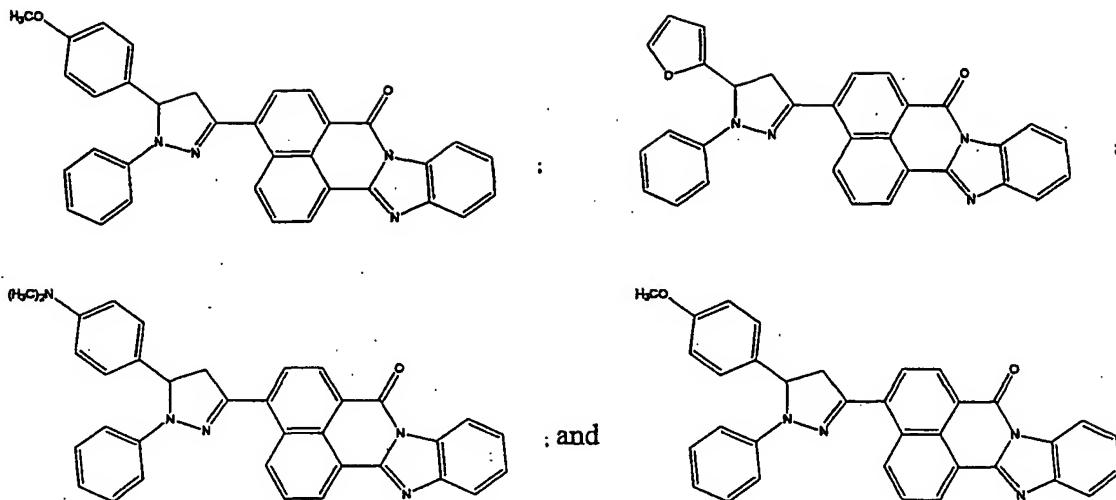
52. The method of claim 41, wherein said color changing material is selected from the group consisting of a PPV polymer, a thiophene-based polymer, an inert polymer with attached luminophor side groups, a fluorene-based polymer, a phenylene-based polymer, a furylene-based polymer, an oligomer with spiro centers, a co-polymer thereof and a combination thereof.

53. The method of claim 41, wherein said color changing material comprises a host compound that is ALQ, and a dopant compound selected from the group

consisting of Coumarin 6, Coumarin 485, Coumarin, 487, Coumarin 490, Coumarin 498, Coumarin 500, Coumarin 503, Coumarin 504, Coumarin 504T, Coumarin 510, Coumarin 515, Coumarin 519, Coumarin 521, Coumarin 521T, Coumarin 522B, Coumarin 523, Coumarin 525, Coumarin 535, Coumarin 540A, Coumarin 545, 5 Coumarin 545T, quinacridone derivatives such as diethyl pentyl quinacridone and dimethyl quinacridone, IDE-102, IDE-105, rubrene, DCJTB, pyrromethane 546, and mixtures thereof.

54. The method of claim 41, wherein said color changing material is a blue-to-red  
10 color changing material and comprises a compound selected from the group  
consisting of:





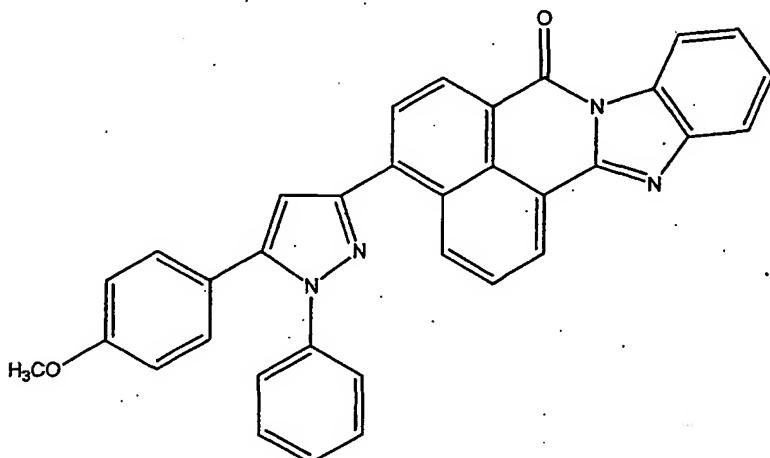
55. The method of claim 41, wherein said color changing material is a blue-to-green color changing material and comprises the compound having the formula:

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25 56. The method of claim 41, wherein said layer comprising a color changing material is less than about 3  $\mu\text{m}$  thick.

57. The method of claim 46, wherein said layer comprising a color changing material is less than about 2  $\mu\text{m}$  thick.

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58. The method of claim 57, wherein said layer comprising a color changing material is less than about 1  $\mu\text{m}$  thick.

5 59. The method of claim 41, wherein said color changing material has an optical density for ultraviolet light of greater than about 1.

60. The method of claim 59, wherein said color changing material has an optical density for ultraviolet light of between about 2 and about 4.

10 61. The method of claim 60, wherein said color changing material has an optical density for ultraviolet light of between about 2 and about 3.

15 62. The method of claim 41, wherein the color changing material in said at least one unexposed area has an absolute quantum efficiency of photoluminescence greater than about 50%.

63. The method of claim 62, wherein said color changing material in said at least one unexposed area has an absolute quantum efficiency of photoluminescence greater than about 70%.

20 64. The method of claim 50, wherein said color changing material in said at least one unexposed area has an absolute quantum efficiency of photoluminescence greater than about 80%.

25 65. The method of claim 41, wherein said protective layer comprises a material selected from the group consisting of  $\text{SiO}_2$ ,  $\text{SiN}$ ,  $\text{MgO}$ , ITO, an organic polymer, a conjugated polymer, a benzophenone, a heat curing epoxy compound, an ultraviolet curing epoxy compound, a spin-on-glass compound, a siloxane and a combination thereof.

30 66. A method of fabricating an up-emitting full-color OLED display device comprising the steps of:

(a) providing a monochromatic OLED display device having a plurality of bottom electrode elements and a surface through which light is emitted;

- (b) depositing a first layer comprising a first color changing material on at least a portion of said surface;
- (c) aligning at least one light absorbing area of a photomask above said first layer with a first electrode element of said monochromatic OLED display device;
- 5 (d) exposing at least one unmasked area of said first layer to light shone through the photomask in the presence of oxygen to leave a first color changing region in a first patterned layer aligned with said first electrode element;
- (e) depositing a first protective layer over said first patterned layer;
- (f) depositing a second layer comprising a second color changing material 10 on said first protective layer;
- (g) aligning at least one light absorbing area of a photomask above said second layer with a second electrode element of said monochromatic OLED display device;
- (h) exposing at least one unmasked area of said second layer to light shone 15 through the photomask in the presence of oxygen to leave a second color changing region in a second patterned layer aligned with said second electrode element; and
- (i) depositing an encapsulation layer over said second patterned layer, wherein the at least one area of said first layer and said second layer under said at least one light absorbing area of the photomask are masked, and wherein said 20 at least one unmasked area of said second layer overlies the first color changing region.

67. The method of claim 66, wherein said at least one light absorbing area of the photomask are each simultaneously aligned with every fourth electrode element of 25 said monochromatic OLED display device.

68. The method of claim 66, wherein said monochromatic OLED display device emits blue light.

30 69. The method of claim 66, wherein said first layer comprises a blue-to-green color changing material and said second layer comprises a blue-to-red color changing material.

70. The method of claim 66, wherein said at least one unmasked area of said first layer and said at least one unmasked area of said second layer each have an absolute quantum efficiency of photoluminescence less than about 5% after said exposing steps.

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71. The method of claim 70, wherein said at least one unmasked area of said first layer and said at least one unmasked area of said second layer each have an absolute quantum efficiency of photoluminescence less than about 1% after said exposing steps.

10

72. The method of claim 66, wherein said at least one unmasked area of said first layer and said at least one unmasked area of said second layer are each substantially transparent to light having a wavelength of between about 400 nm and 750 nm after said exposing steps.

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73. The method of claim 66, wherein said exposing steps are each performed for between about 1 min. and 3 min.

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74. The method of claim 66, wherein said light used in step (d) and step (h) has a wavelength of between about 250 nm and 420 nm.

25

75. The method of claim 66, wherein at least one of said first said color changing materials and said second color changing materials is selected from the group consisting of a PPV polymer, a thiophene-based polymer, an inert polymer with attached luminophor side groups, a fluorene-based polymer, a phenylene-based polymer, a furylene-based polymer, an oligomer with spiro centers, a co-polymer thereof and a combination thereof.

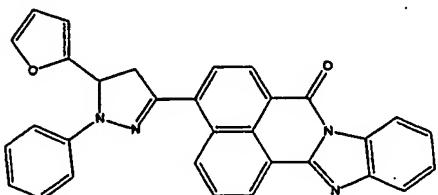
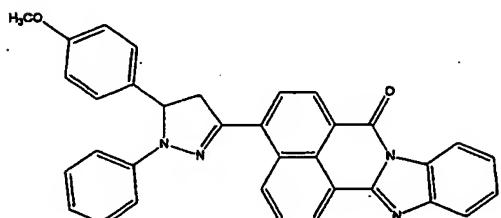
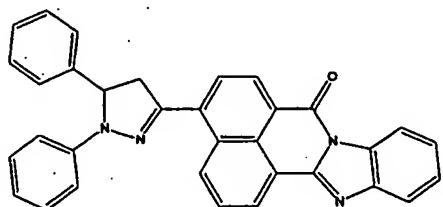
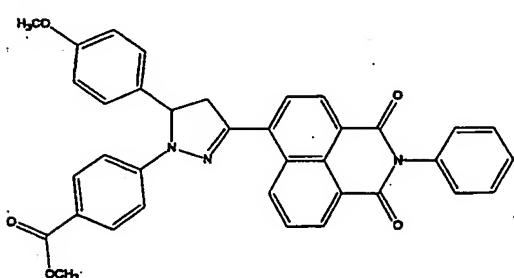
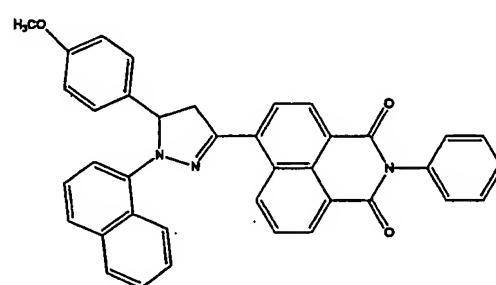
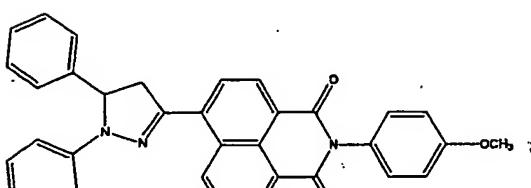
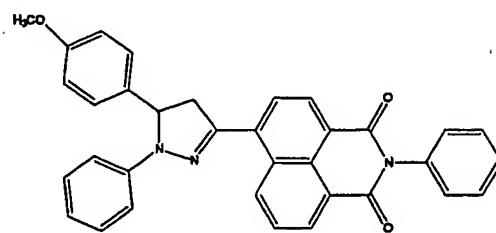
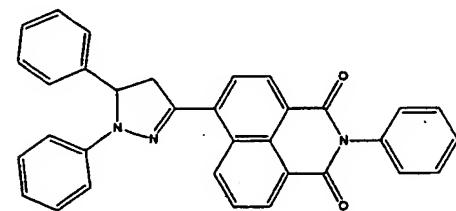
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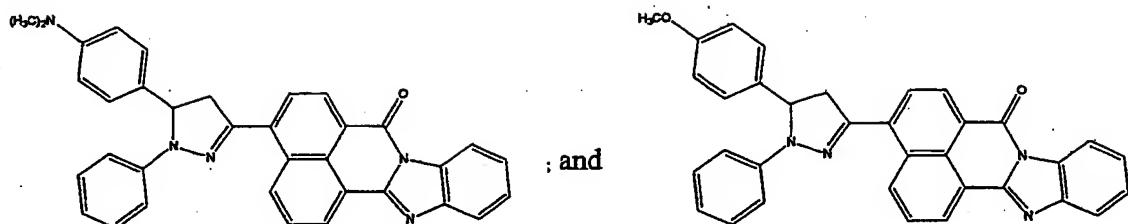
76. The method of claim 66, wherein at least one of said first color changing materials and said second color changing materials comprises a host compound that is ALQ, and a dopant compound selected from the group consisting of Coumarin 6, Coumarin 485, Coumarin 487, Coumarin 490, Coumarin 498, Coumarin 500, Coumarin 503, Coumarin 504, Coumarin 504T, Coumarin 510, Coumarin 515, Coumarin 519, Coumarin 521, Coumarin 521T, Coumarin 522B, Coumarin 523,

Coumarin 525, Coumarin 535, Coumarin 540A, Coumarin 545, Coumarin 545T, quinacridone derivatives such as diethyl pentyl quinacridone and dimethyl quinacridone, IDE-102, IDE-105, rubrene, DCJTB, pyrromethane 546, and mixtures thereof.

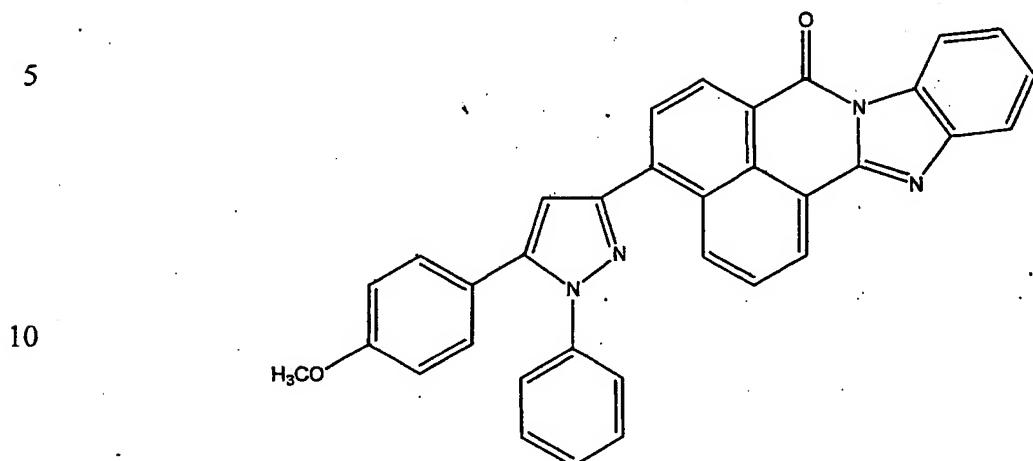
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77. The method of claim 69, wherein said blue-to-red color changing material comprises a compound selected from the group consisting of:





78. The method of claim 69, wherein said blue-to-green color changing material comprises the compound having the formula:



15 79. The method of claim 66, wherein said first layer and said second layer are each independently less than about 3  $\mu\text{m}$  thick.

80. The method of claim 79, wherein said first layer and said second layer are each independently less than about 2  $\mu\text{m}$  thick.

20  
81. The method of claim 80, wherein said first layer and said second layer are each independently less than about 1  $\mu\text{m}$  thick.

82. The method of claim 66, wherein said first color changing material and said  
25 second color changing material each independently has an optical density for  
ultraviolet light of greater than about 1.

83. The method of claim 82, wherein said first color changing material and said second color changing material each independently has an optical density for ultraviolet light of between about 2 and about 4.

5 84. The method of claim 83, wherein said first color changing material and said second color changing material each independently has an optical density for ultraviolet light of between about 2 and about 3.

10 85. The method of claim 66, wherein the at least one masked area of said first layer and said second layer each independently has an absolute quantum efficiency of photoluminescence of greater than about 50%.

15 86. The method of claim 85, wherein the at least one masked area of said first layer and said second layer each independently has an absolute quantum efficiency of photoluminescence of greater than about 70%.

20 87. The method of claim 86, wherein the at least one masked area of said first layer and said second layer each independently has an absolute quantum efficiency of photoluminescence of greater than about 80%.

25 88. The method of claim 66, wherein said first protective layer and said second protective layer each independently comprise a material selected from the group consisting of  $\text{SiO}_2$ ,  $\text{SiN}$ ,  $\text{MgO}$ , ITO, an organic polymer, a conjugated polymer, a benzophenone, a non-fluorescent organic dye, a heat curing epoxy compound, an ultraviolet curing epoxy compound, a spin-on-glass compound, a siloxane and a combination thereof.

30 89. The method of claim 66, wherein said encapsulation layer comprises a material selected from the group consisting of  $\text{SiO}_2$ , perylene and  $\text{Al}_2\text{O}_3$ .

90. The method of claim 68, wherein the at least one masked area of said first layer and said second layer each independently absorb about 95% of the blue light emitted from said monochromatic OLED display device.

91. The method of claim 66, wherein the at least one masked area of said first layer and said second layer each independently has an absolute quantum efficiency of photoluminescence of greater than about 50%.

5 92. The method of claim 91, wherein the at least one masked area of said first layer and said second layer each independently has an absolute quantum efficiency of photoluminescence of greater than about 70%.

10 93. The method of claim 92, wherein the at least one masked area of said first layer and said second layer each independently has an absolute quantum efficiency of photoluminescence of greater than about 80%.

94. The method of claim 66, wherein the full-color OLED display device has a sub-pixel size of less than about 50  $\mu\text{m}$ .

15 95. The method of claim 94, wherein the full-color OLED display device has a sub-pixel size of less than about 25  $\mu\text{m}$ .

20 96. The method of claim 95, wherein the full-color OLED display device has a sub-pixel size of less than about 10  $\mu\text{m}$ .

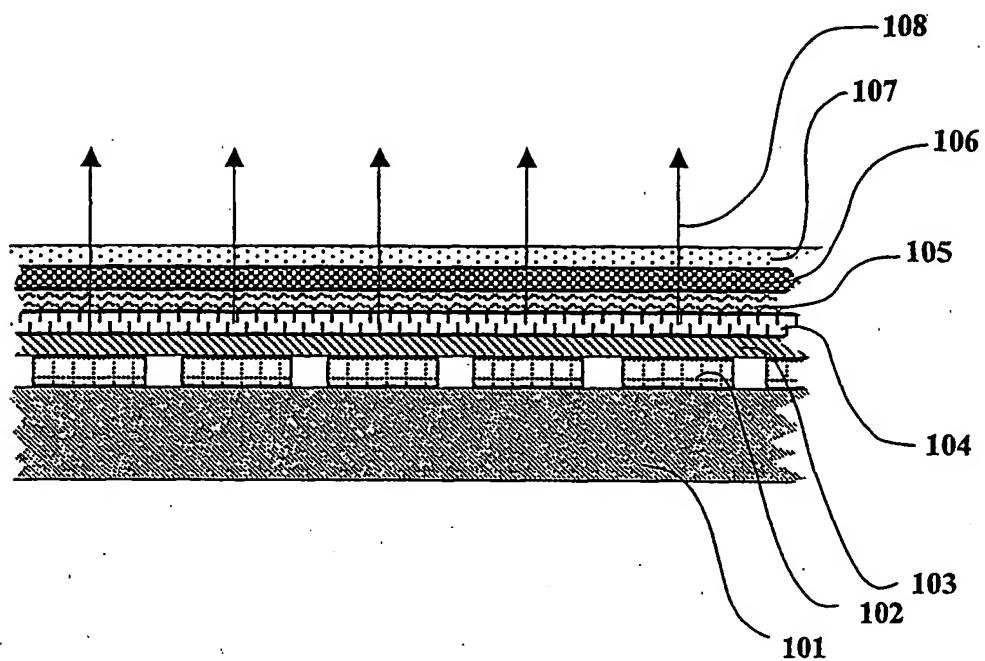


FIG. 1

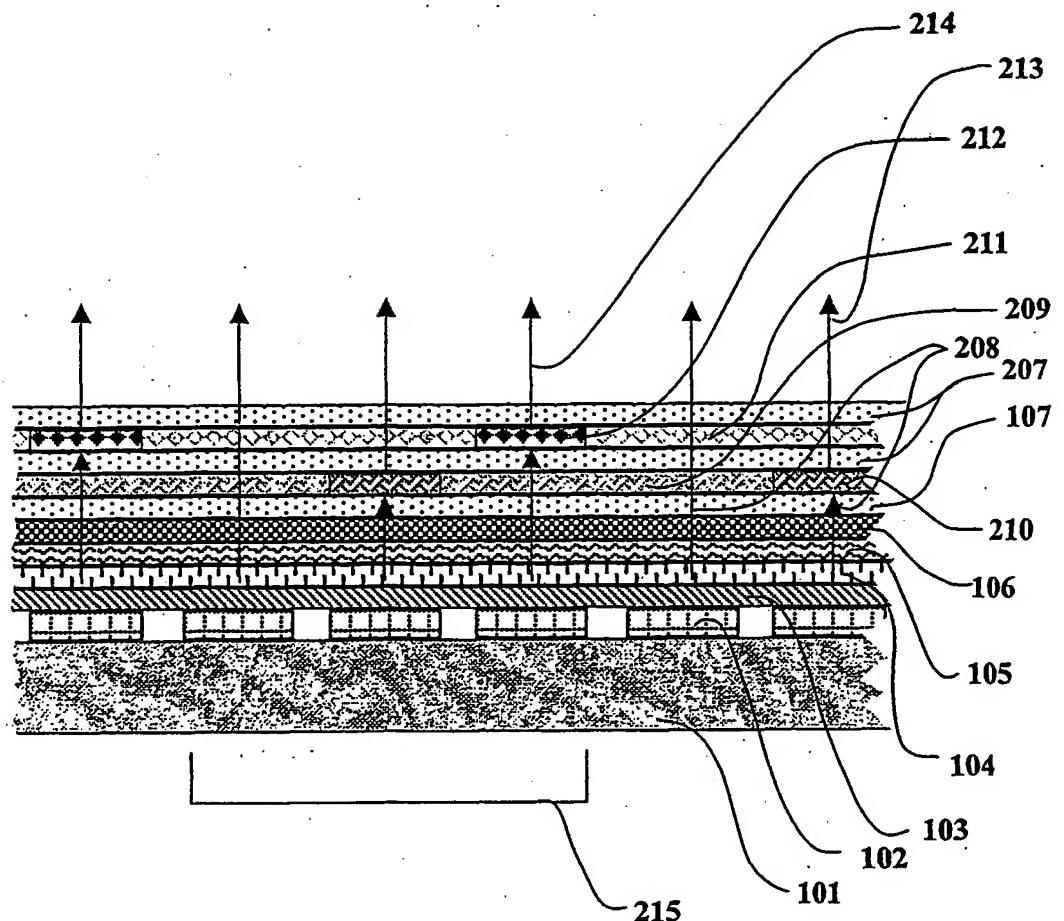
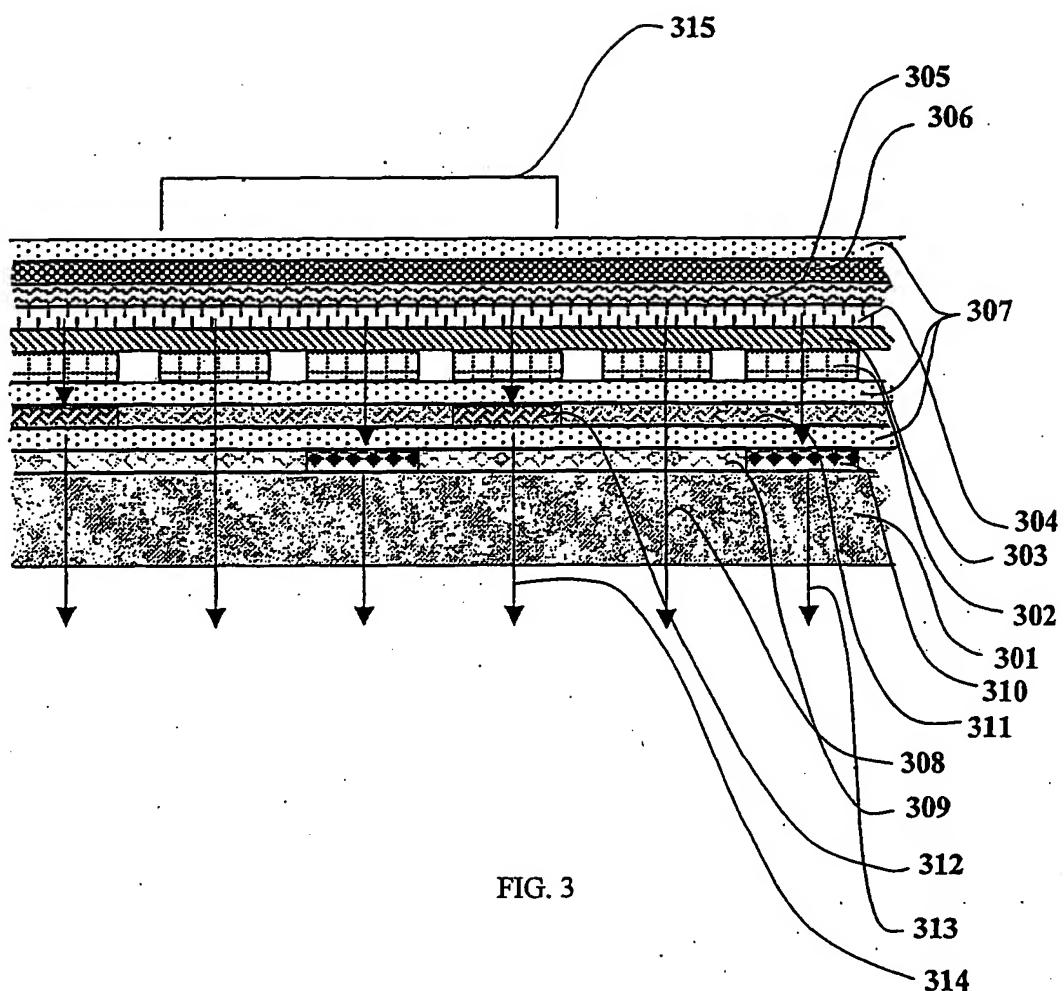


FIG. 2



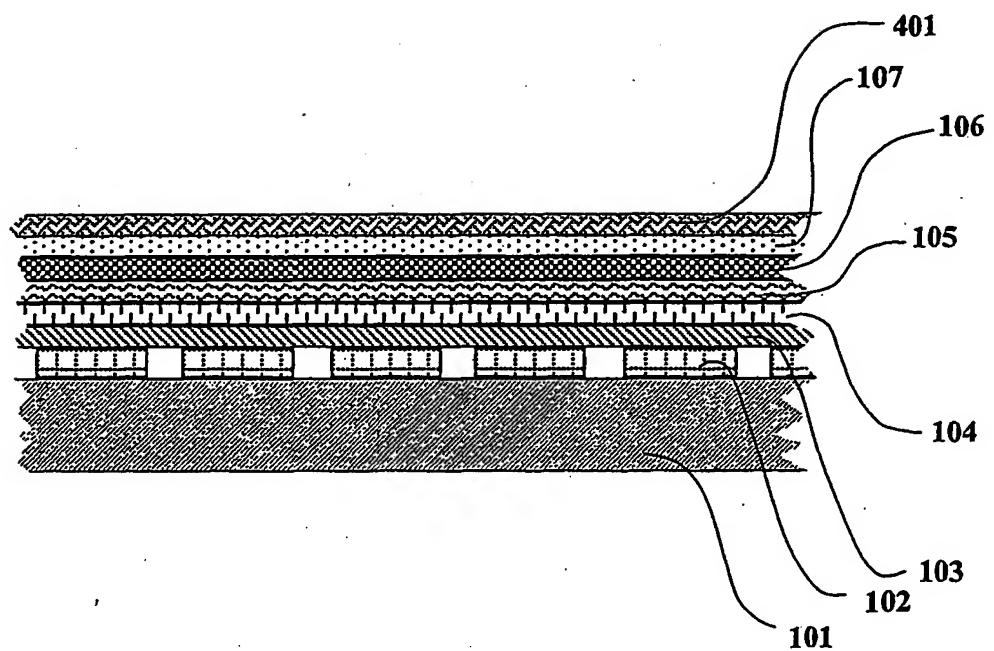


FIG. 4

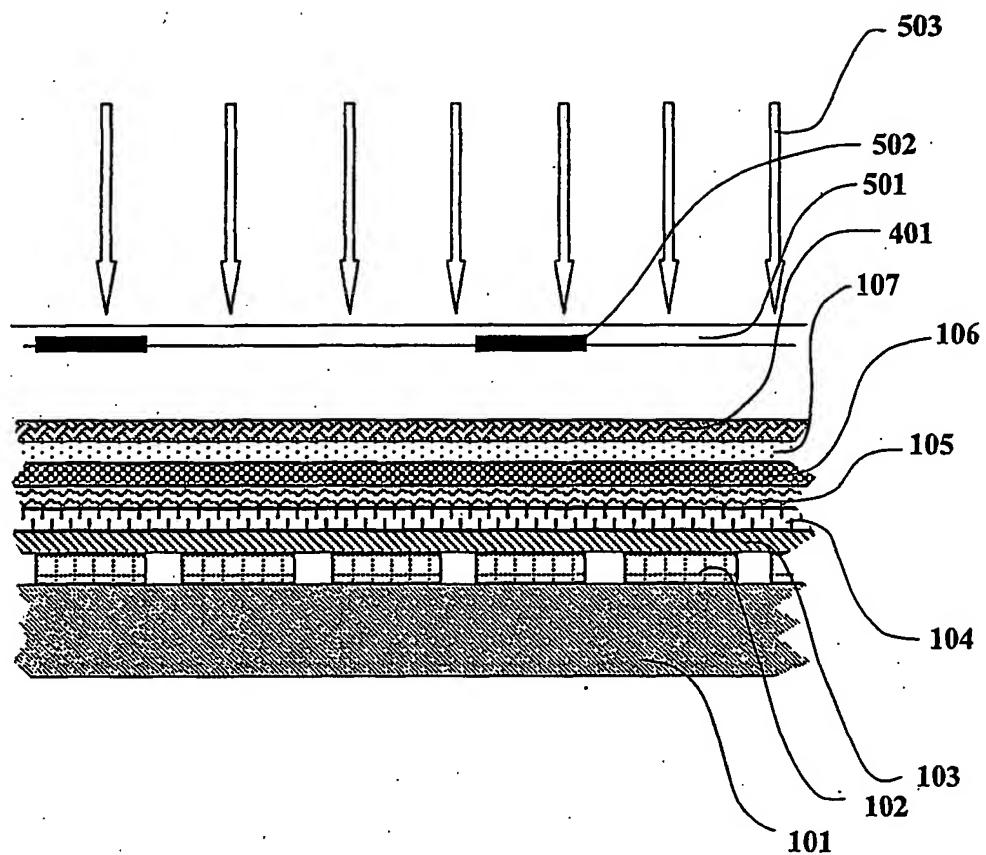


FIG. 5

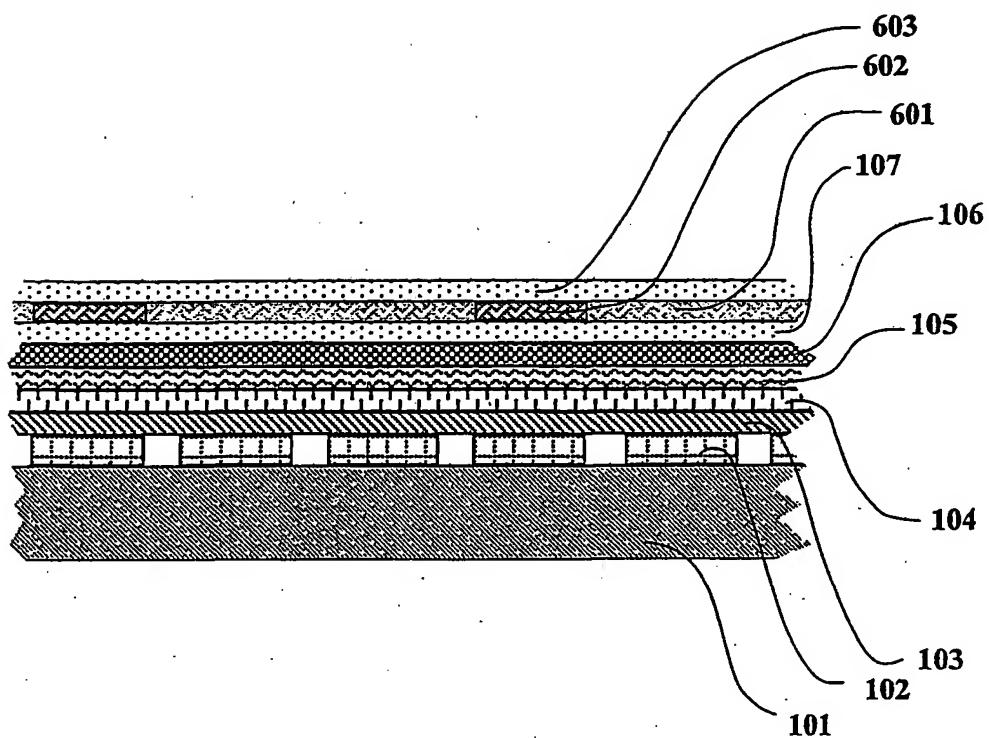


FIG. 6

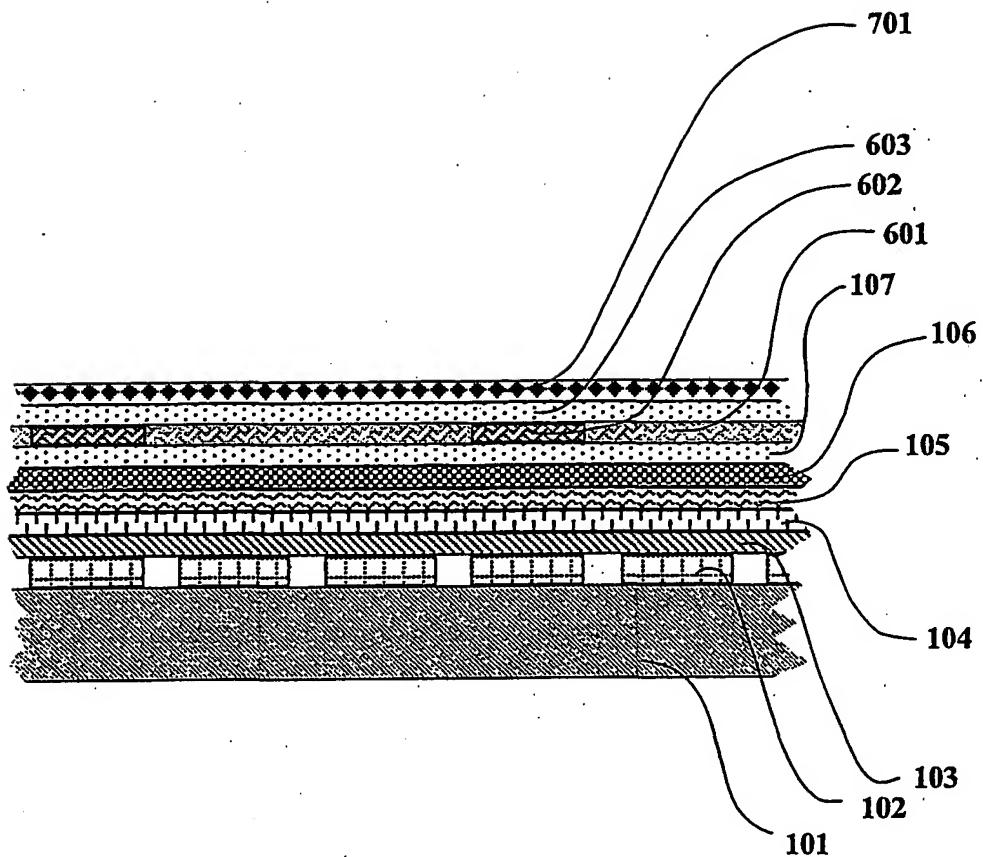


FIG. 7

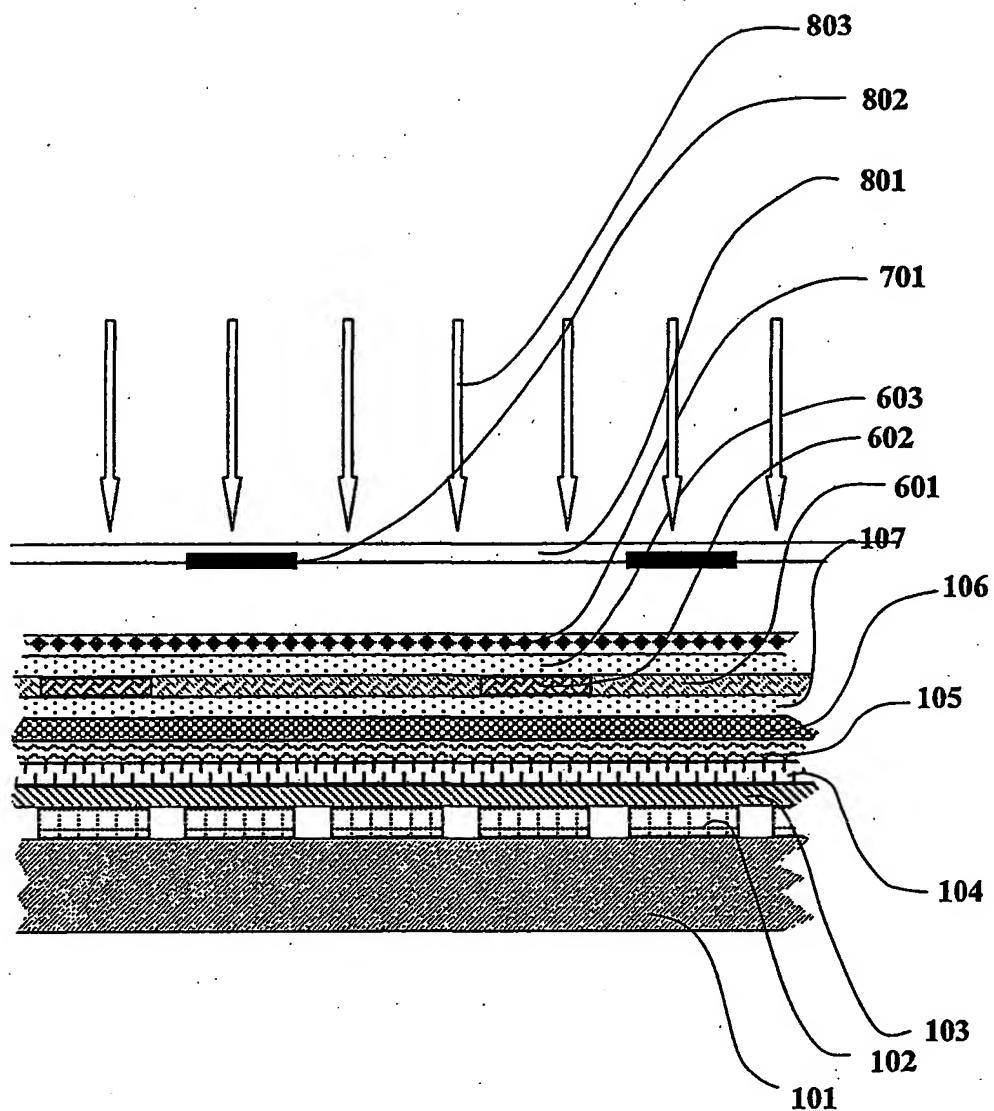


FIG. 8

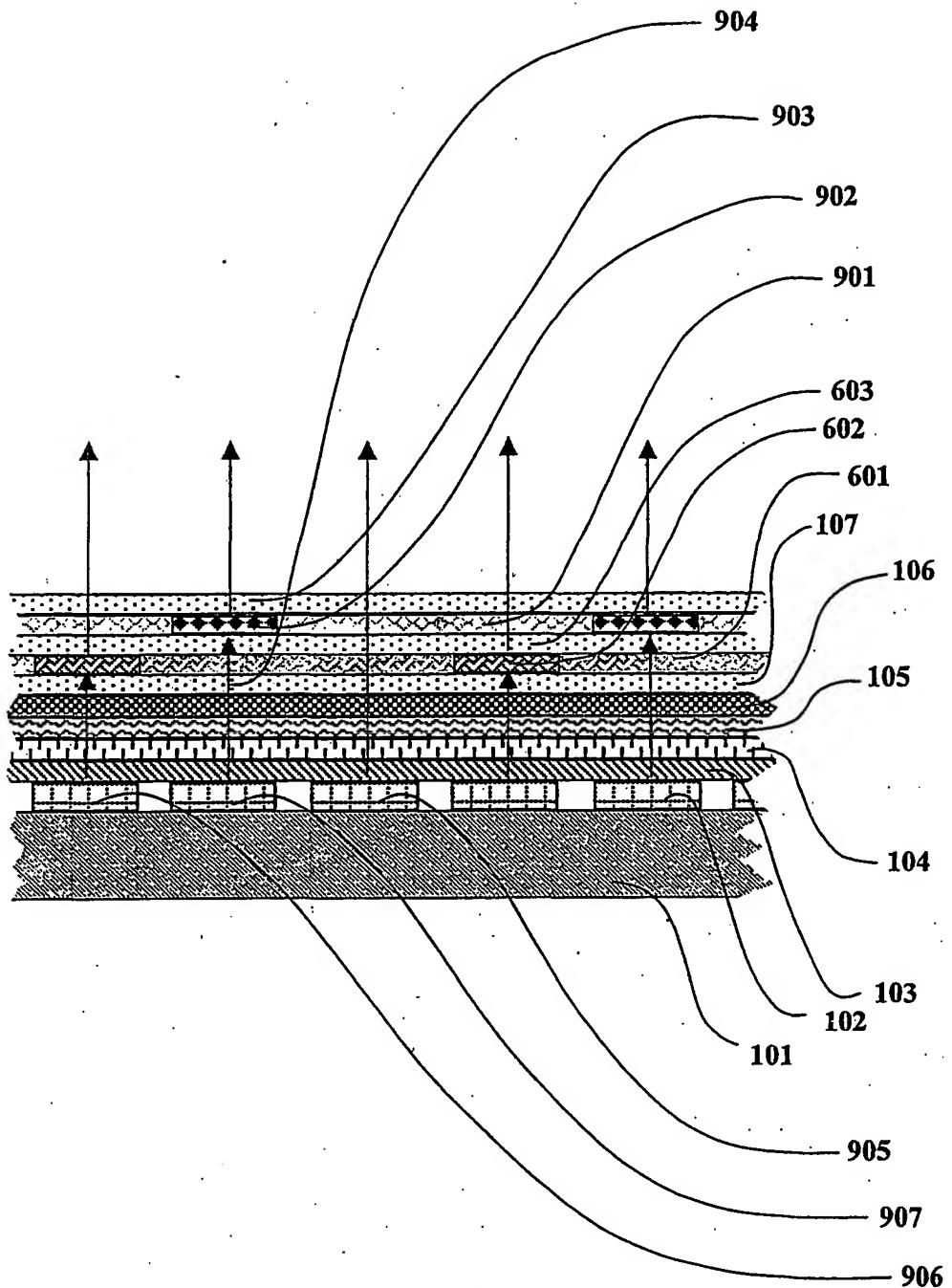


FIG. 9

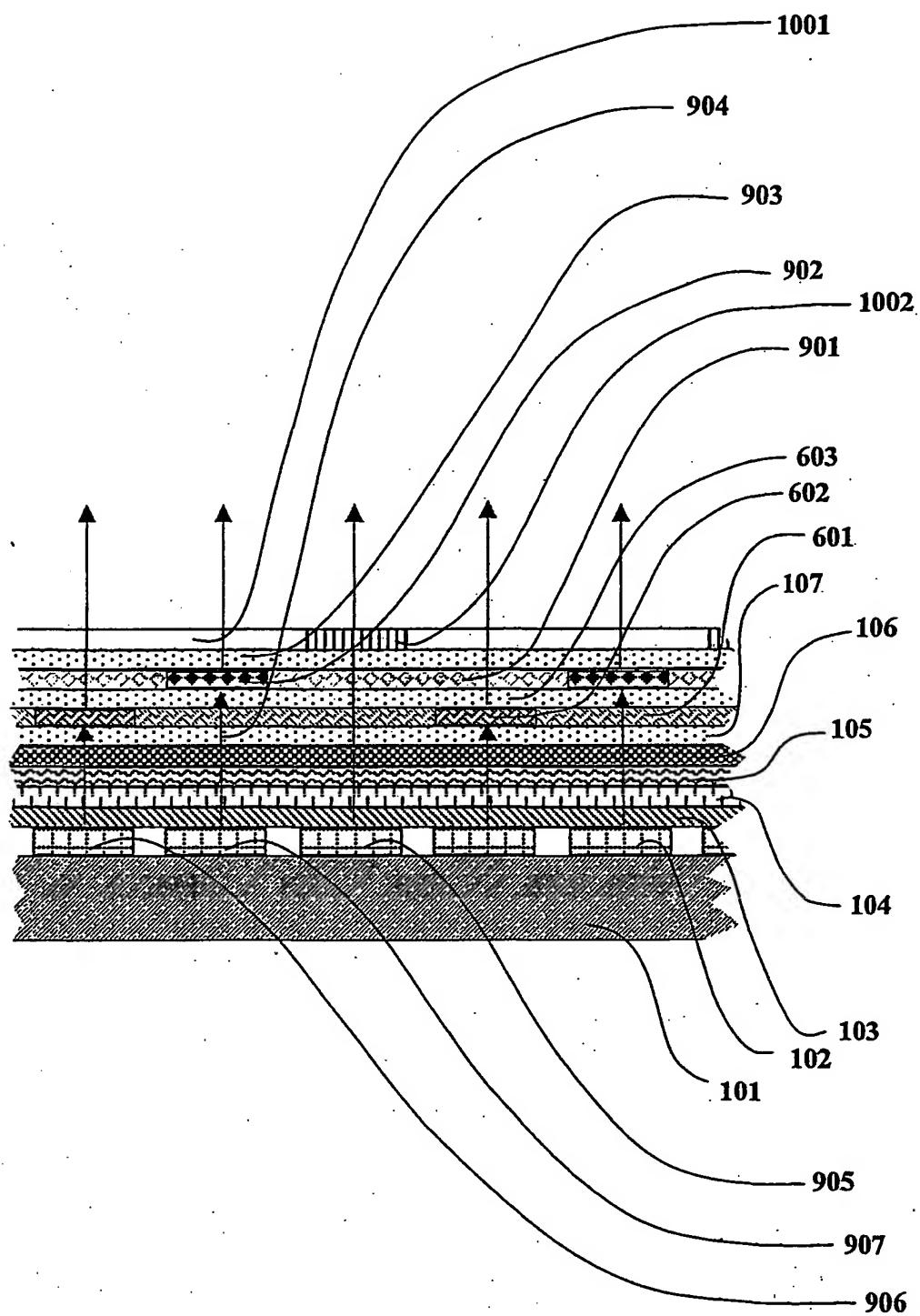


FIG. 10

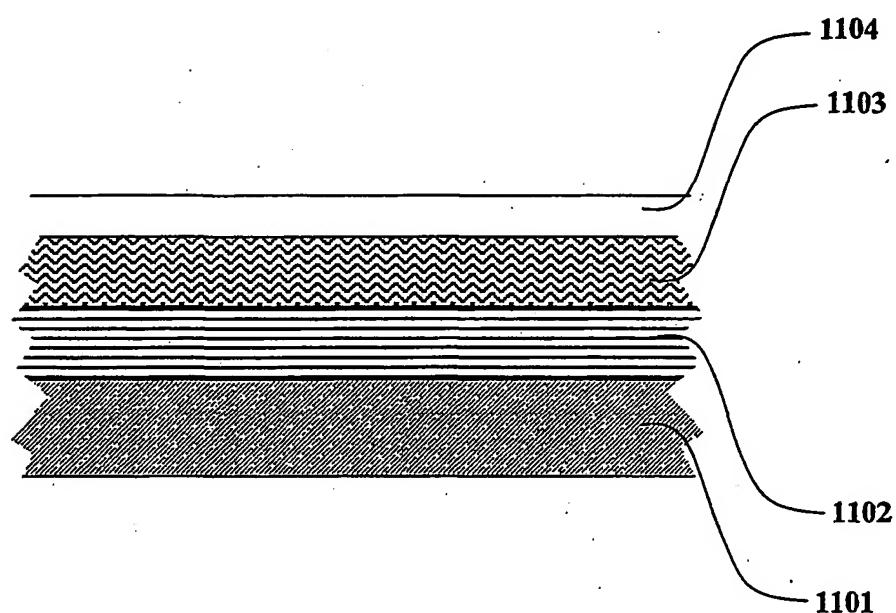


FIG. 11

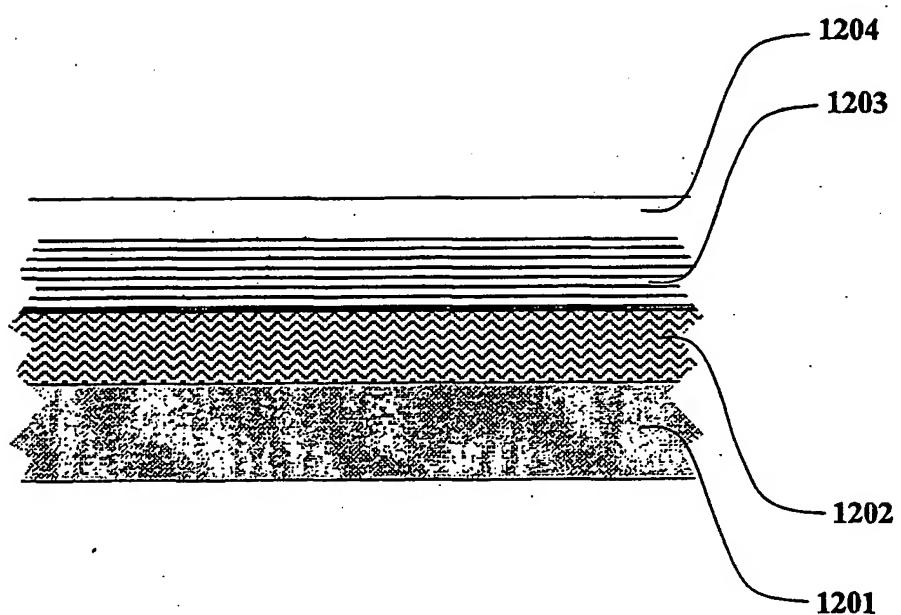


FIG. 12

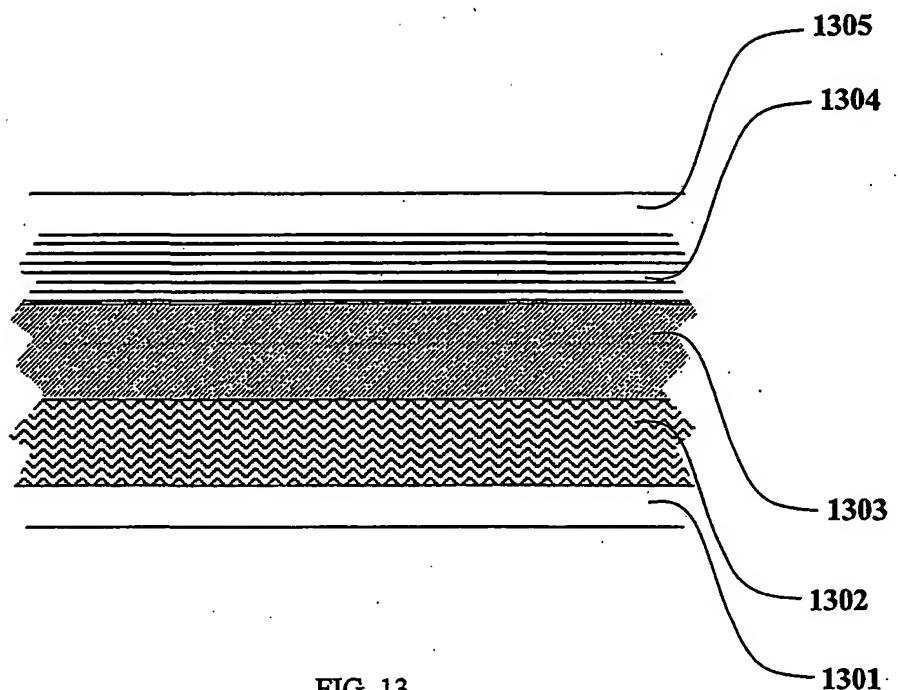


FIG. 13

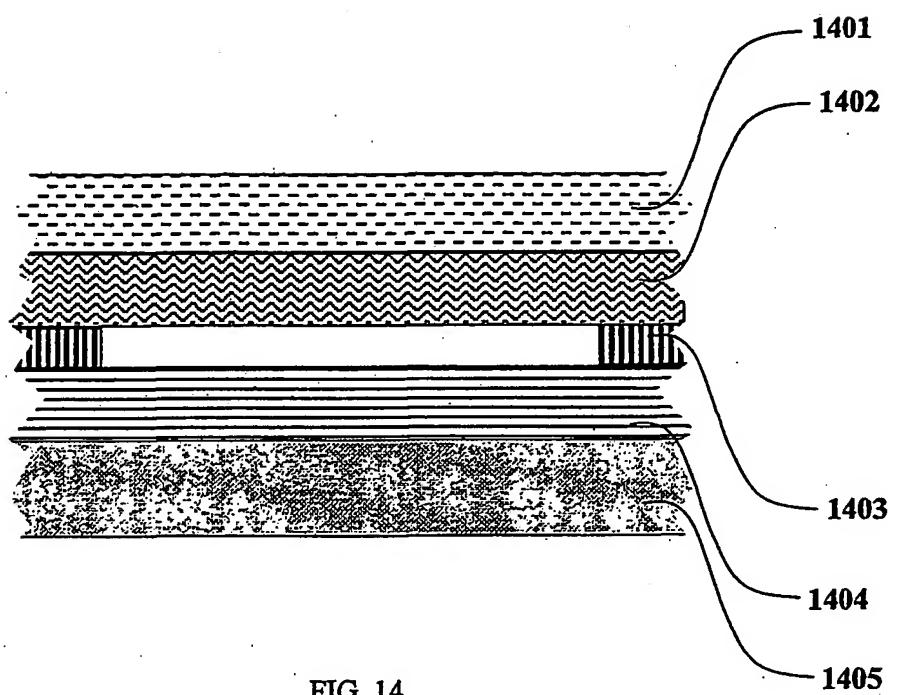


FIG. 14

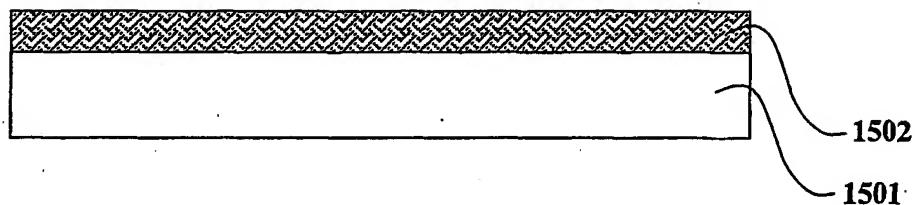


FIG. 15

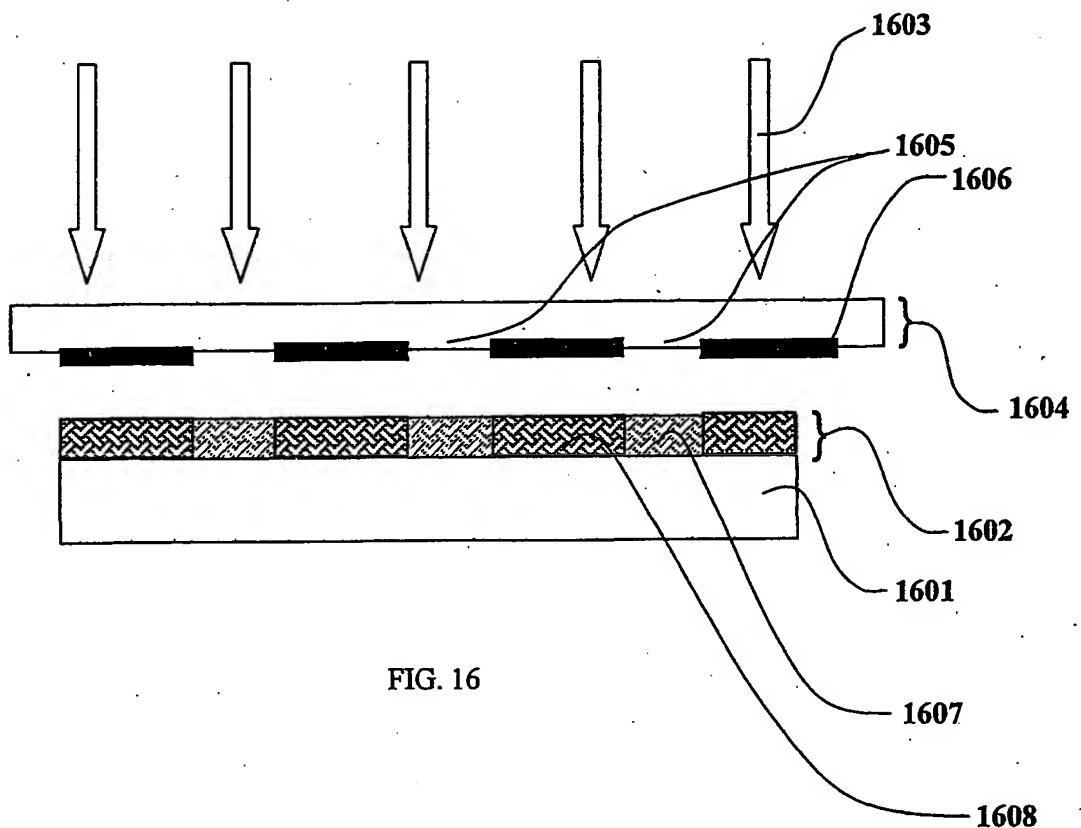


FIG. 16

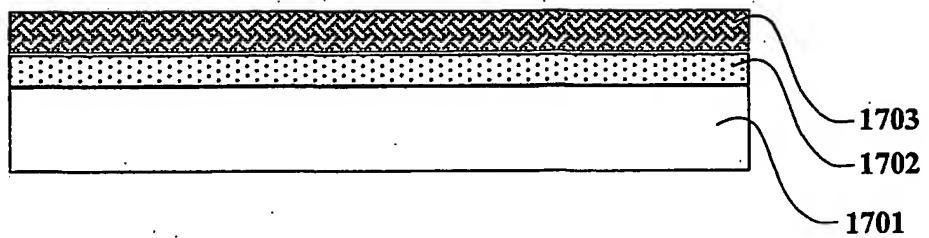


FIG. 17

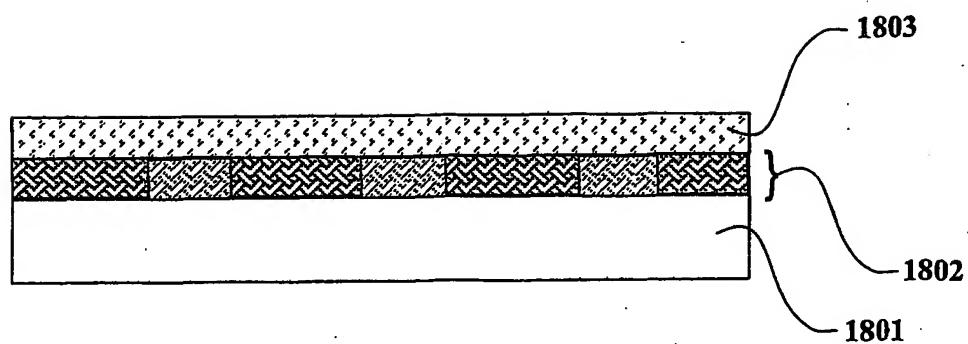


FIG. 18